The PHENIX Charmonium Program

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4th Berkeley School on Collective Dynamics in High Energy Collisions

Lawrence Berkeley Laboratory
May 14-18, 2012

PHENIX Charmonium Goals

Studying the effect of **color screening** in the QGP on the production rate of charmonium was a major PHENIX design consideration.

Ideally, we would like measurements for the J/ψ, ψ' and χ_c - three states with different **binding energies** and **radii**.

In practice, at RHIC the J/ψ is relatively easy to observe in A+A collisions, and the ψ' and χ_c are **very difficult**, even in p+p collisions.

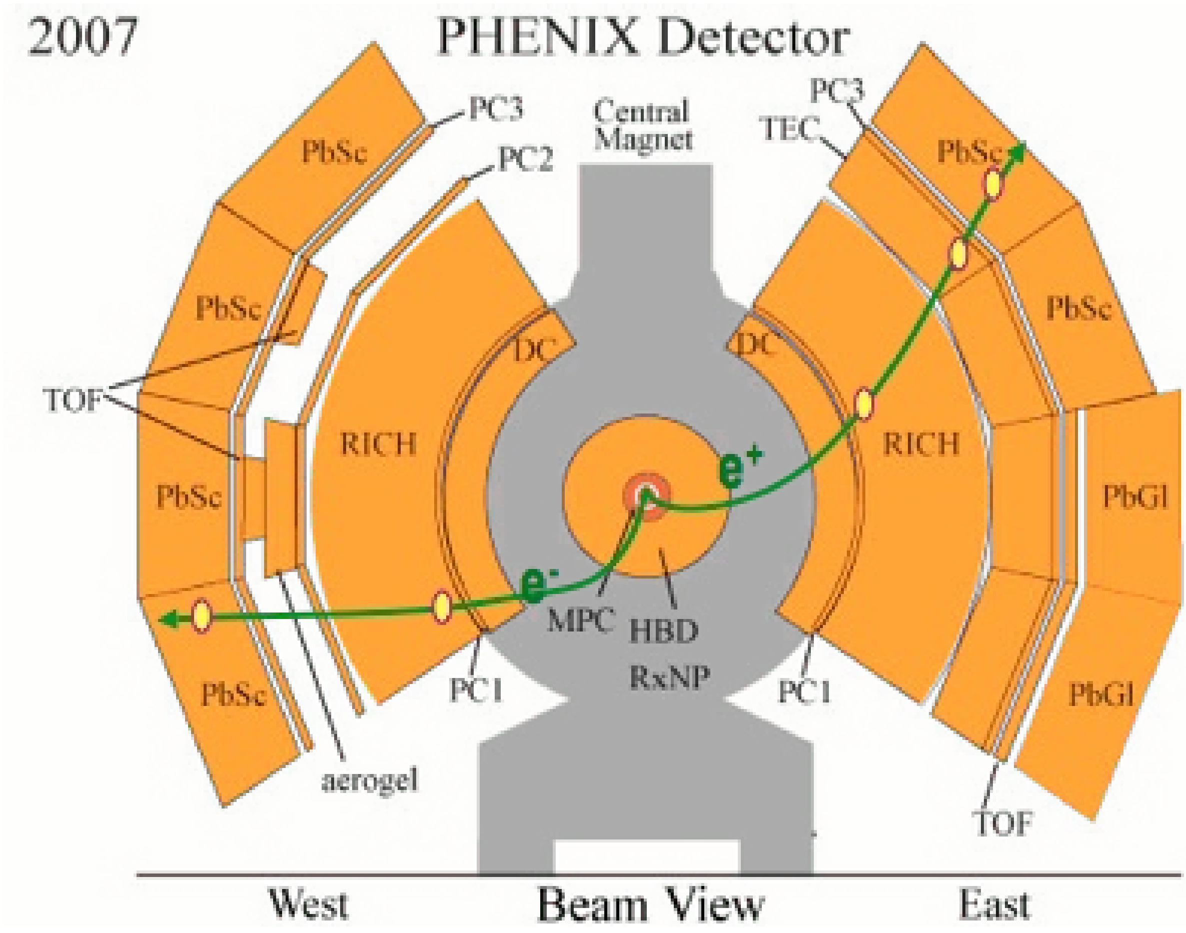
So our studies of the effect of the medium on charmonium in A+A collisions have been confined to the J/ψ, at least so far.

In the meantime, it has become clear that J/ψ production in **d+Au collisions** is very interesting in its own right, as well as being a baseline for A+A.

Observing Vector Mesons via Dielectron Decays

Central arms (mid rapidity, as of 2008 Run)

- Drift chamber + Pad Chamber (momentum measurement)
- Ring Imaging Cherenkov detector (hadron rejection ~ 100)
- Electromagnetic Calorimeter (E/p → hadron rejection ~ 10)

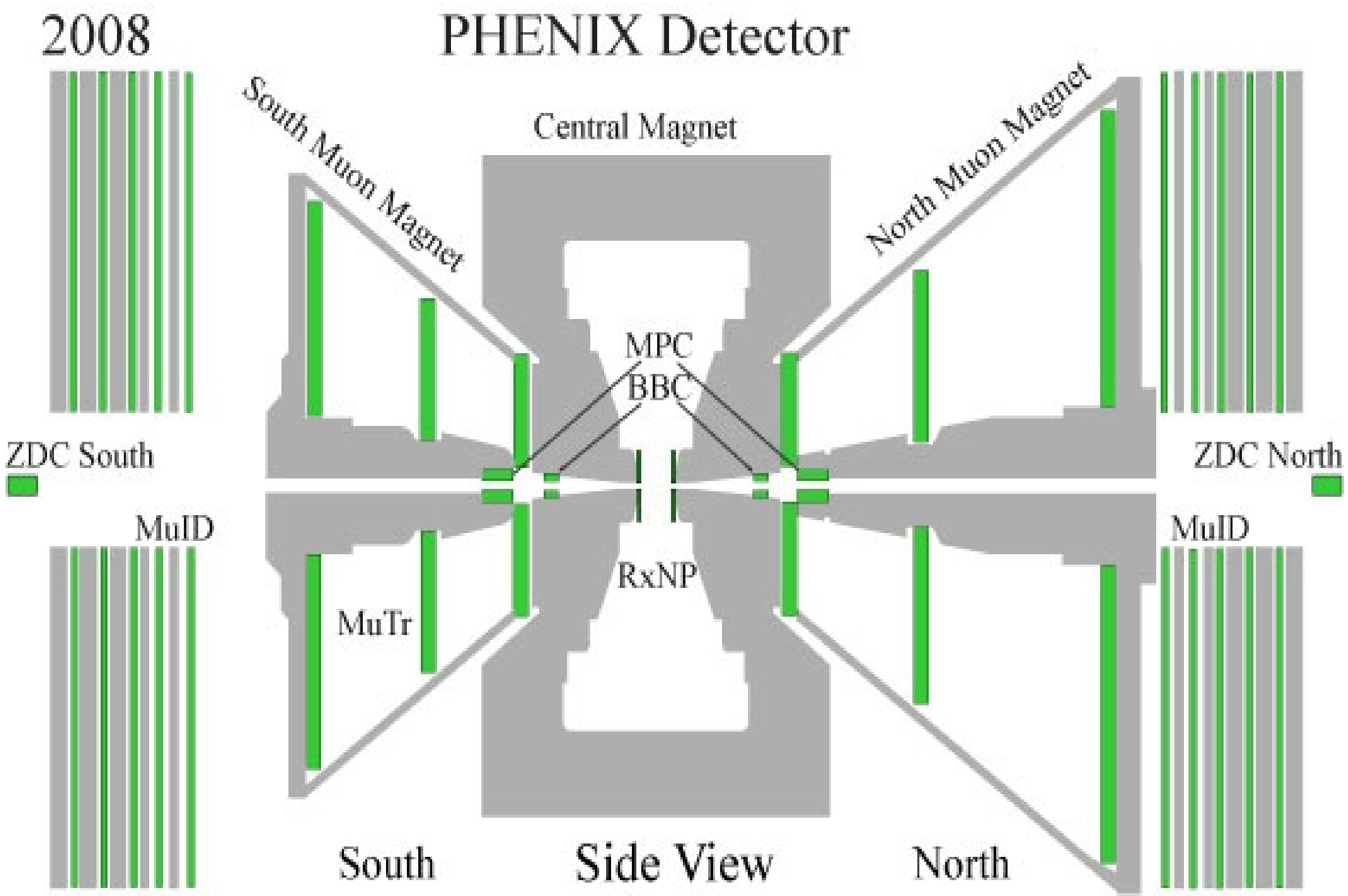


D, B → $e^{\pm}$
J/ψ → e^+e^-
$-0.35 < y < 0.35$
$\Delta\Phi = \pi$

Observing Vector Mesons via Dimuon Decays

Muon arms (forward and backward rapidity)

- Muon Tracker (momentum)
- Steel absorber (shower out hadrons)
- Muon Identifier (layered [steel / wire chambers] for muon ID)



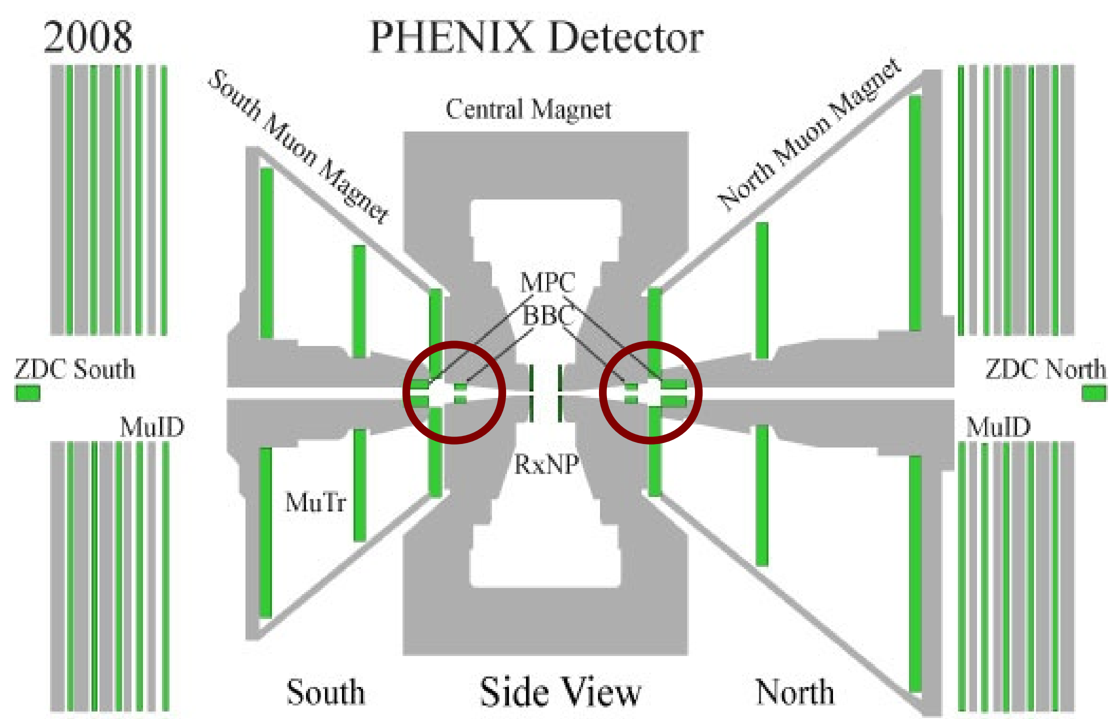
D, B → $\mu^{\pm}$
J/ψ → $\mu^{+}\mu^{-}$
$-2.2 < y < -1.2$
$1.2<y<2.4$
$\Delta\,\Phi = 2\pi$

The Beam-Beam Counters (BBC)

The Beam-Beam Counters cover the pseudorapidities $-3.9 < \eta < -3.0$ and $3.0 < \eta < 3.9$. Each has 64 **quartz Cherenkov counters**.

They detect soft charged particles produced in a collision, and provide:

- The collision location along the beam axis, from the time difference between BBC North and South
- The collision centrality for A+A collisions, from the signal size



Triggering

The BBC provides our **event trigger**. We require one (or, in Au+Au, two) hits in each, and we accept collisions within 30 cm of the center of the detector.

Collisions producing a small number of charged particles can miss one or both BBC detectors.

- For p+p collisions the average BBC trigger efficiency is 50%
- For d+Au collisions it is 88%
- For Au+Au collisions it is 93%

But: If an event contains a **hard process** (such as J/ψ production) it produces more soft particles – **increasing the BBC trigger efficiency**. So:

- Measure the BBC trigger bias in p+p using events triggered on high p_T π^0's (it increases to 75%)
- Simulate the trigger bias for A+A collisions as a function of collision centrality in a Glauber model

Measuring collision centrality

To study the **energy density** dependence, we need an event by event measurement of a quantity that **relates to** energy density. The magnitude of the combined signal due to soft particles in the BBC provides this.

We relate centrality to number of nucleon participants (N_{part}), or number of binary collisions (N_{coll}), using a **Glauber model** (Miller et al. Ann. Rev. Nucl. Part. Sci. 57 (2007) 205)

The BBC signal is assumed to have a **negative binomial distribution** probability distribution. The parameters of the NBD are fitted to data at large N_{part} – where trigger efficiency is 1 – and the fitted distribution is compared with the BBC signal at low N_{part} to get the **trigger efficiency**. The NBD distribution and trigger efficiency are then used in the Glauber model to make centrality bins and determine <Npart> and <Ncoll> for each bin.

Important: we do not **measure** N_{part}, N_{coll} or energy density- the BBC signal is only a **proxy** for them that is affected strongly by statistical fluctuations - more on this later.

A systematic program

Observe charmonium production as a function of:

- Collision centrality
- Rapidity
- Transverse momentum

Trying to cover, in each case, as much of the relevant range as possible – since differences in centrality and kinematics emphasize different processes.

We need to study the baseline cross sections, as well as the A+A ones:

- Charmonium production mechanisms in **p+p** collisions
- Modification when produced in a nuclear target (**d+Au**)
- Modification when produced in HI collisions (**Au+Au, Cu+Cu**)

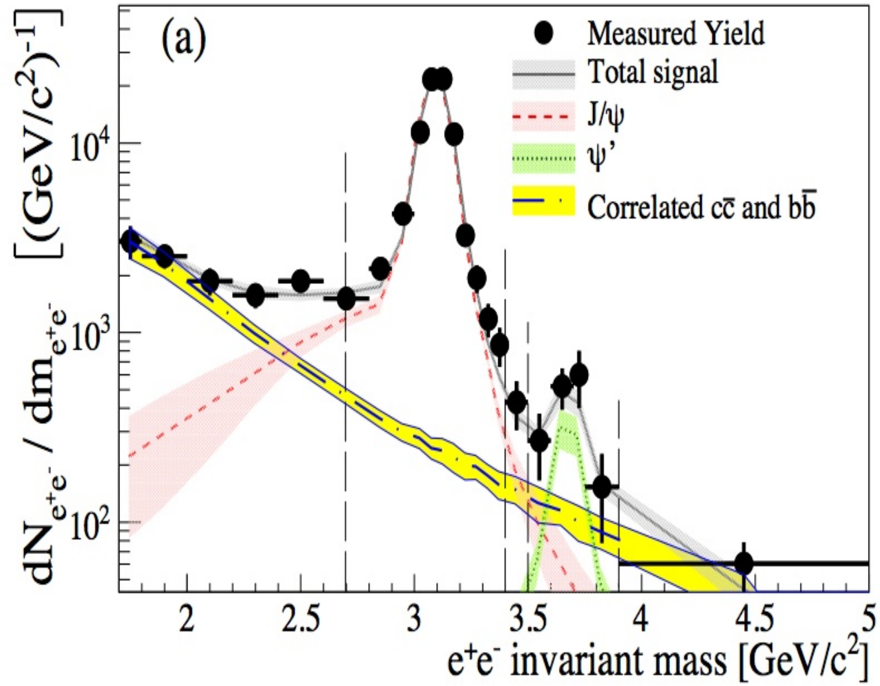
p+p collisions

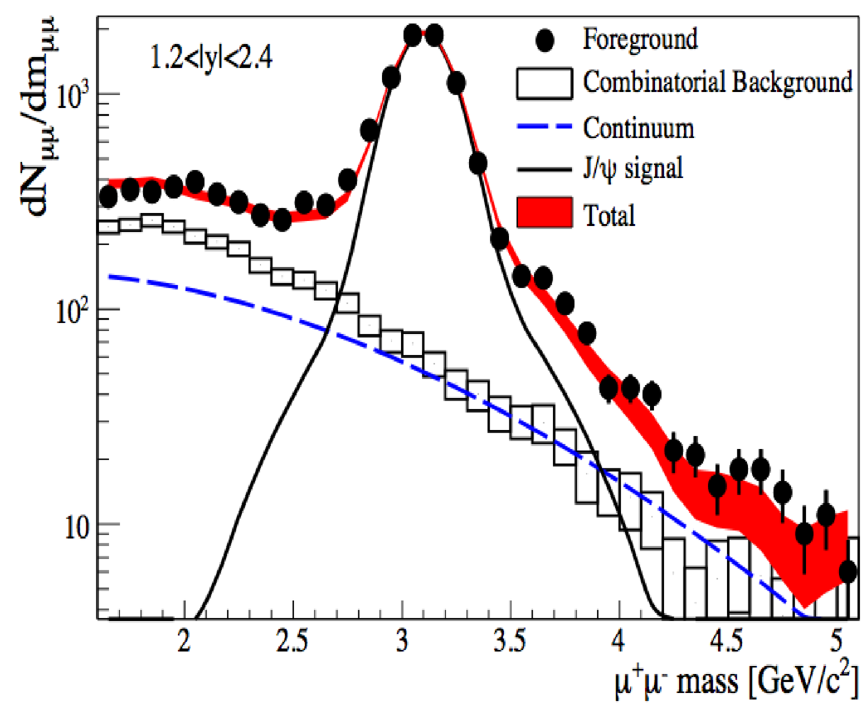
Invariant mass distributions from reconstruction of e^+e^- pairs at midrapity (top) and $\mu^+\mu^-$ pairs at forward/backward rapidity (bottom).

The mass spectrum is made from all electrons or muons in each event. The **combinatorial background** due to unrelated pairs has to be estimated.

For the dielectrons, combinatorial background is estimated using **all like sign pairs**.

For dimuons the S/B is poorer, so the combinatorial background is estimated by **mixing tracks between events** (to improve the statistical precision).





p+p collisions – rapidity distribution

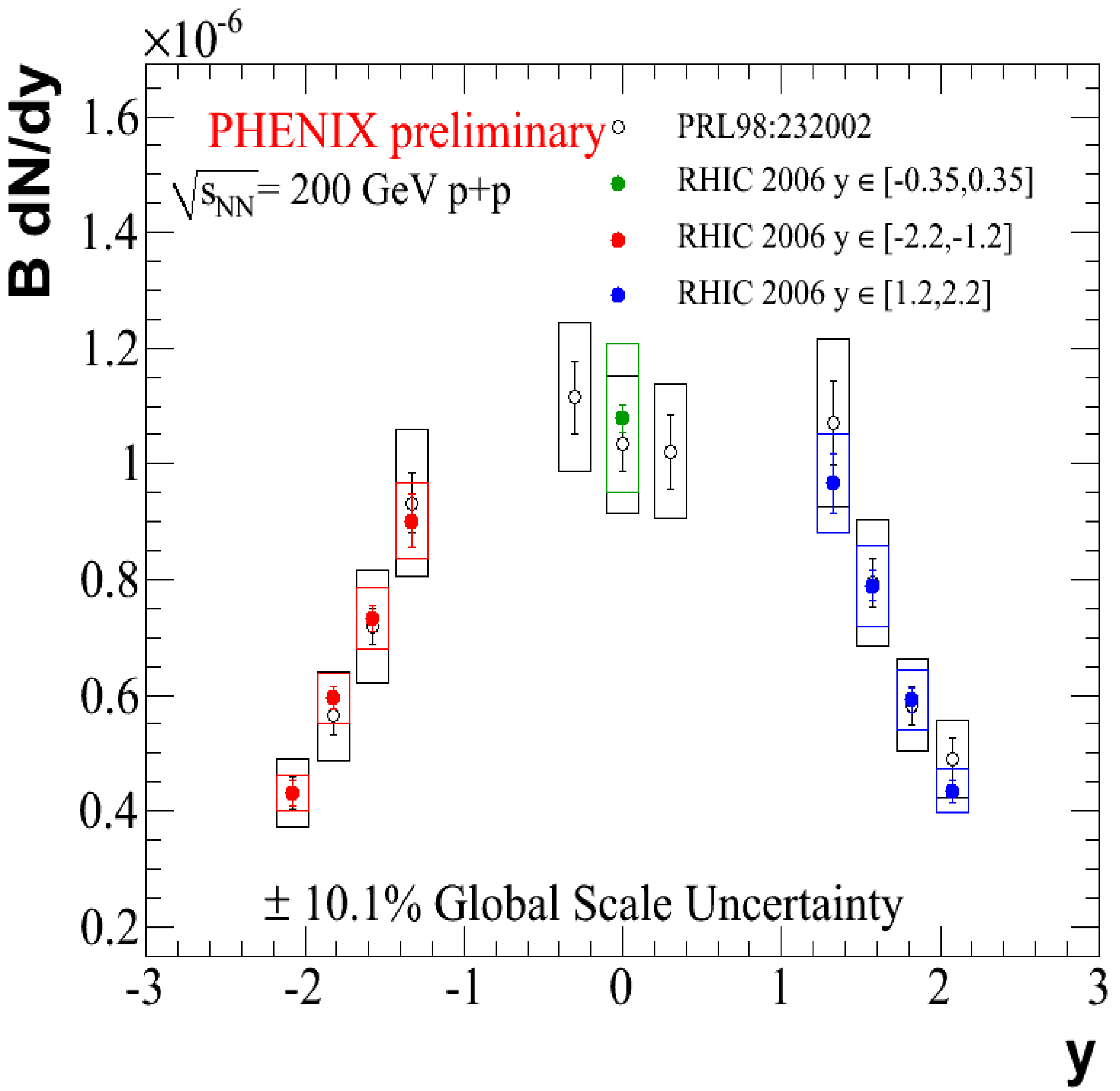
Before we can measure modifications in heavy ion collisions, we have to measure the baseline cross sections in p+p collisions. Start with the rapidity distribution.

This is a comparison of data from the 2006 Run with data from the 2005 Run.

- **Vertical bars** are point-to-point uncertainties.
- **Boxes** are correlated systematic uncertainties.
- The **global** uncertainty is quoted on the figure.

The data provide a good cross section measurement:

$$BR\,\sigma_{J/\psi} = 180.7 \pm 2 \pm 12\, nb$$



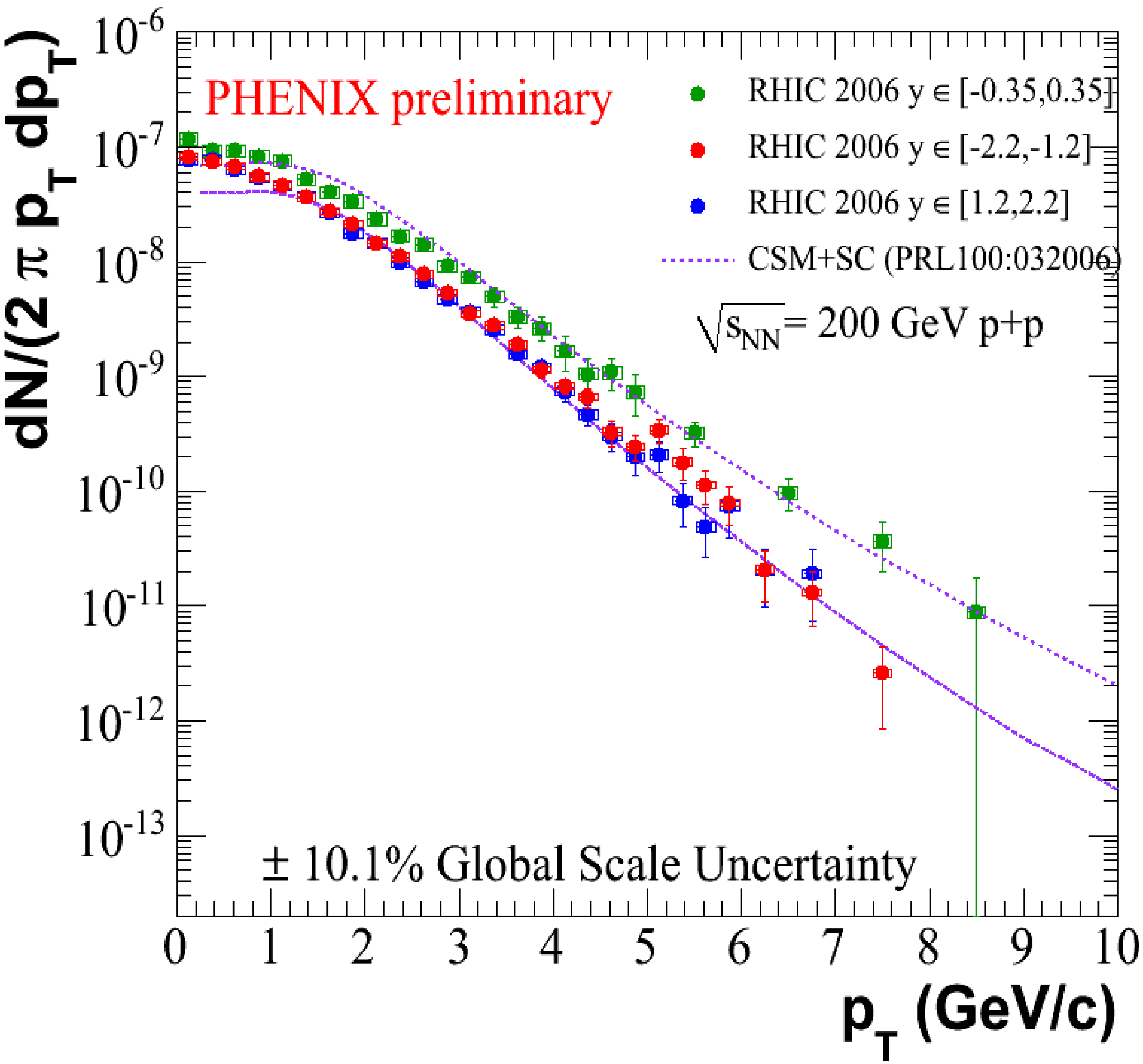
p+p collisions – transverse momentum

The p_T distributions for the three PHENIX spectrometers.

The distribution is noticably harder at midrapidity.

Fortunately, it is the same at forward and backward rapidity.

These distributions (appropriately binned or integrated in p_T and y) provide the denominators for all of our R_{dAu} data.

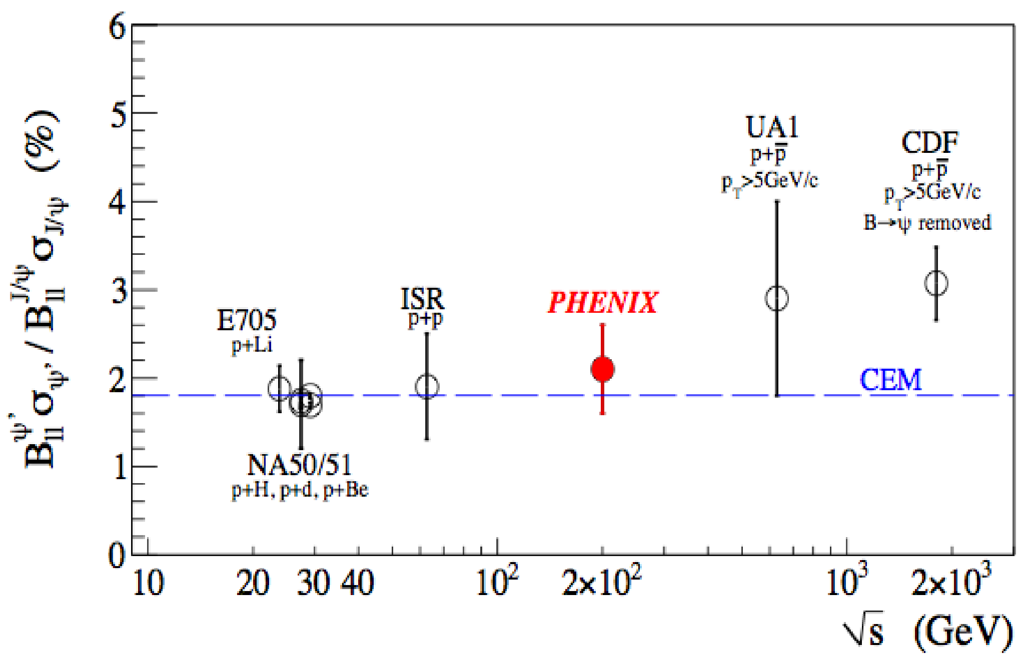


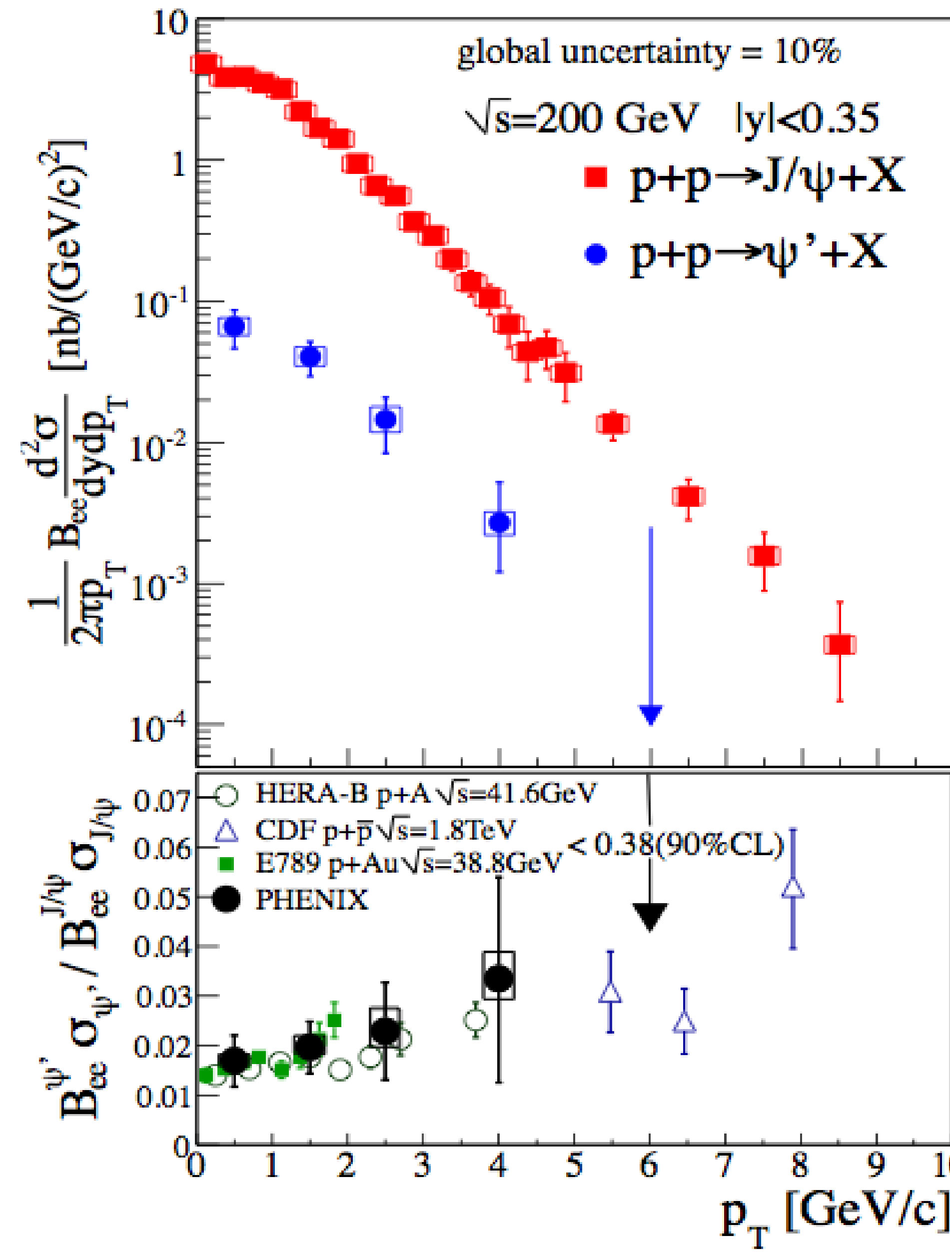
p+p collisions – the ψ'

In p+p collisions, we resolve $\psi' \to e^+e^-$ from $J/\psi \to e^+e^-$ for dielectrons.

The feed down fraction from the ψ' to the J/ψ is measured to be:

$$F_{\psi'}^{J/\psi} = \frac{B_{J/\psi}^{\psi'}\sigma_{\psi'}}{\sigma_{J/\psi}} = (9.7 \pm 2.4)$$



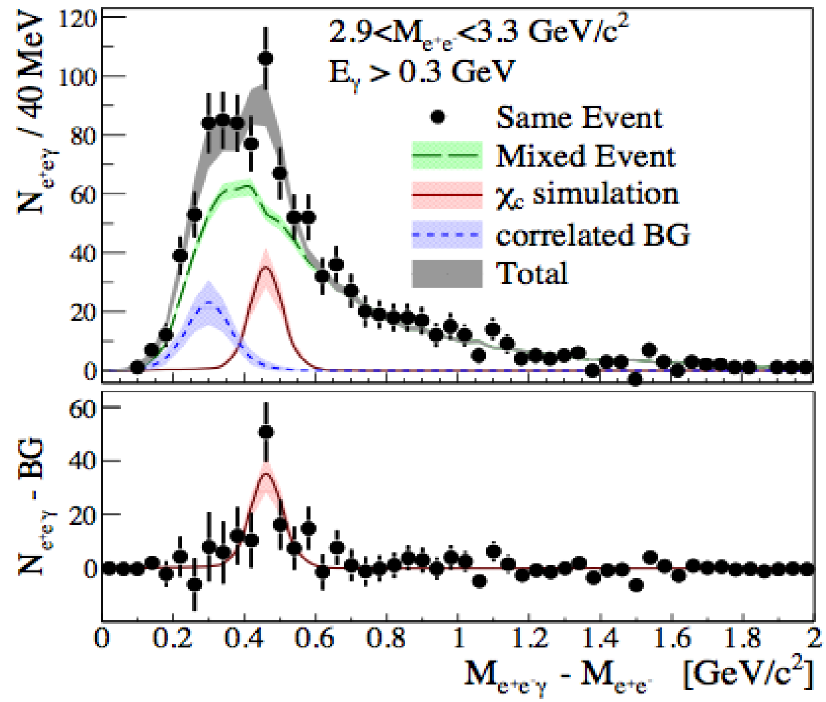


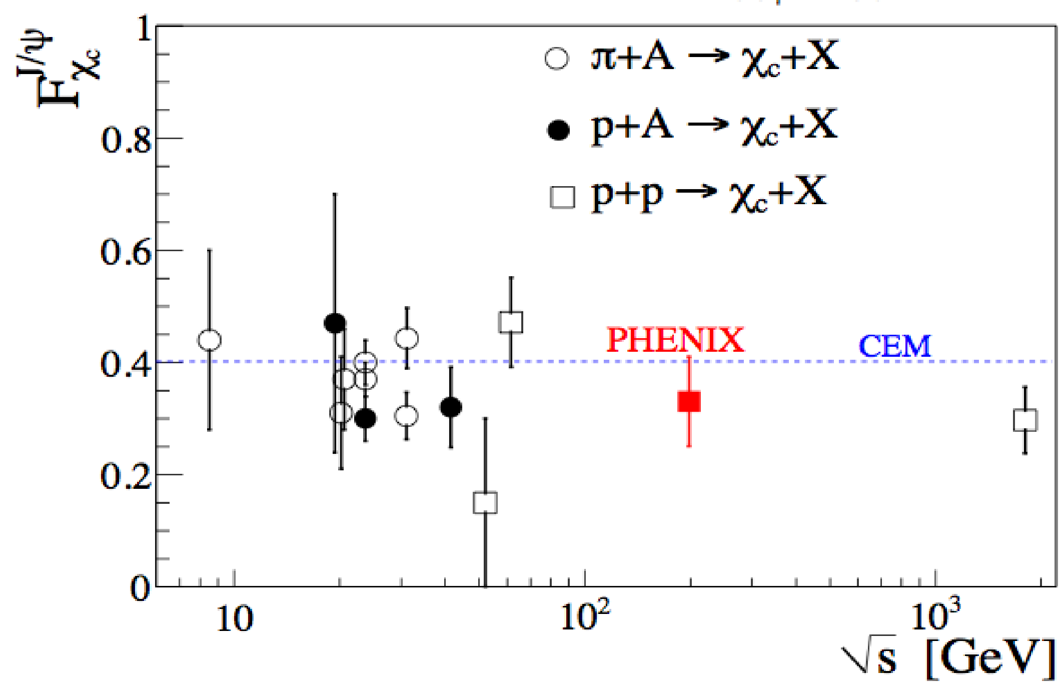
p+p Collisions – the χ_c

In p+p collisions, we see a signal at midrapidity from $\chi_c \rightarrow \gamma + J/\psi \rightarrow \gamma + e^+e^-$ decays.

The feed down fraction from the χ_c to the J/ψ is measured to be:

$$F_{\chi_C}^{J/\psi} = \frac{N_{\chi_C}}{N_{J/\psi}} \frac{1}{\epsilon_{\chi_C} / \epsilon_{J/\psi}} = (32 \pm 9)\%$$





p+p Collisions – J/ψ feed down from the ψ' and χ_c

Combining the results for the feed down from the ψ' and χ_c to the J/ψ we find a total of

$$F^{J/\psi}_{\psi' + \chi_c} = 0.42 \pm 0.09$$

That means that if the ψ' and χ_c respond differently to **CNM** and **hot matter** effects – as they most likely do – this has to be accounted for when trying to understand J/ψ modification in A+A collisions.

A+A collisions

PHENIX has measured J/ψ cross sections in:

Au+Au collisions (200 GeV - RHIC runs 4, 7, 10, and 11)
Au+Au collisions (64 & 39 GeV - RHIC run 11)

Cu+Cu collisions (200 GeV - Run 5)

d+Au collisions (200 GeV - Runs 3 and 4)

Let's look first at the modification in **Au+Au at 200 GeV**.

Au+Au collisions at 200 GeV

To look for the effects of high energy densities, we need to measure the nuclear modification, defined as:

$$R_{AA} = \frac{\sigma^{AA}_{J/\psi}}{\langle N_{coll} \rangle \sigma^{pp}_{J/\psi}}$$

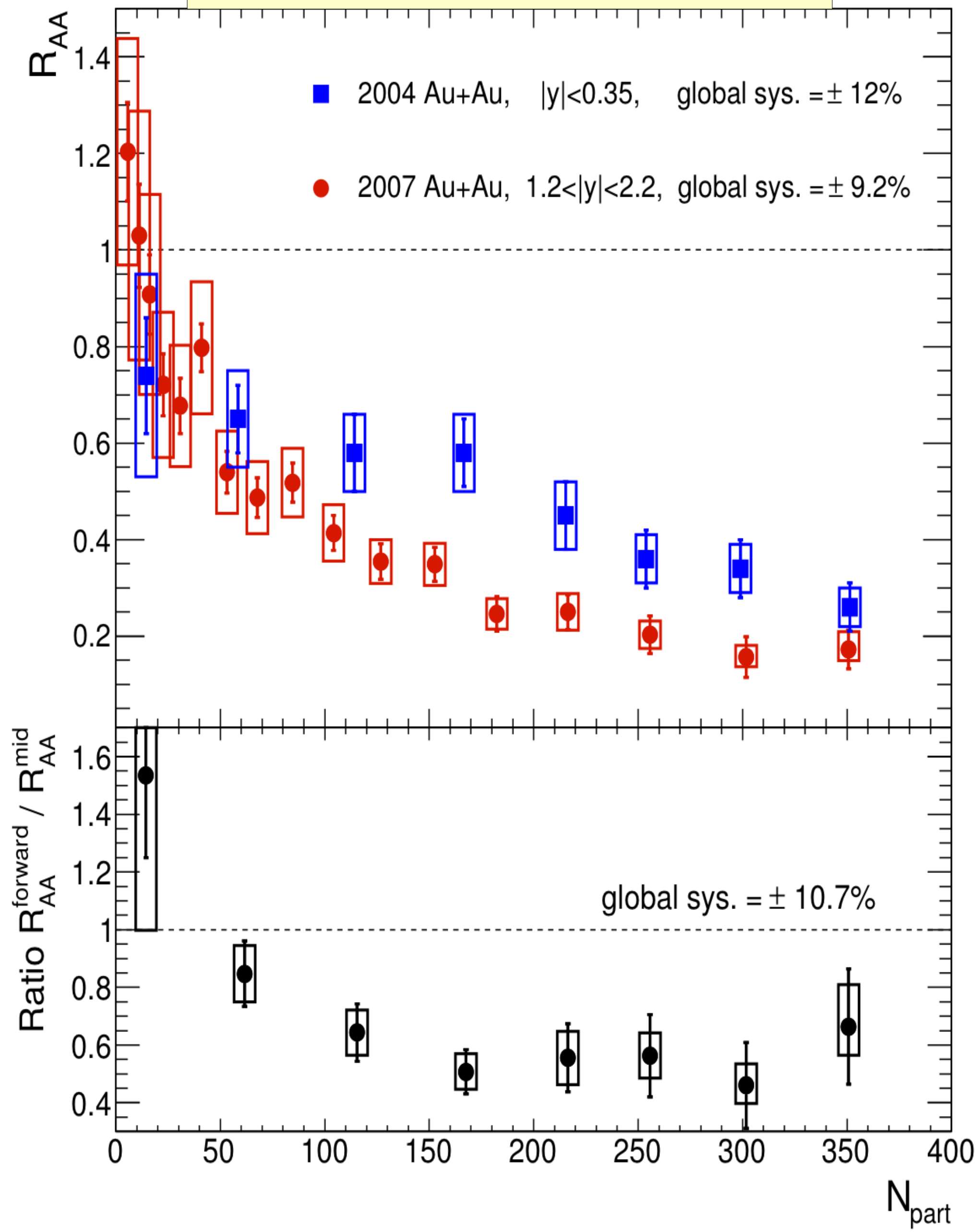
Where σ can stand for any differential cross section (eg. dσ/dy or dσ/dp_T), $\langle N_{coll} \rangle$ is the average number of binary collisions for the sample of A+A collisions. For a hard process with no modification of the cross section, we would get $R_{AA} = 1$, since hard processes scale with binary collisions.

We want to measure R_{AA} as a function of energy density. In practice, we measure R_{AA} versus **collision centrality**.

From a Glauber calculation we estimate $\langle N_{part} \rangle$ for each centrality bin, and plot the data against that.

Centrality Dependence of R_{AA} for 200 GeV Au+Au

PRC 84 054912 (2011)



The nuclear modification versus N_{part} is shown for mid rapidity (blue) and for forward/backward rapidity (red).

Two features stand out:

The suppression for the most central collisions is very strong

$R_{AA} \sim 0.25$ at $y = 0$

$R_{AA} \sim 0.17$ at $|y| = 1.7$

The suppression is systematically stronger at $|y| = 1.7$ (see bottom panel)

p_T dependence of R_{AA} for 200 GeV Au+Au collisions

For p_T dependence of R_{AA} we use centrality bins 0-20%, 20-40%, 40-60% and 60-92%.

Even then, we run out of statistics at ~ 5 GeV/c for Au+Au.

Of course, low p_T is where much of the action is.

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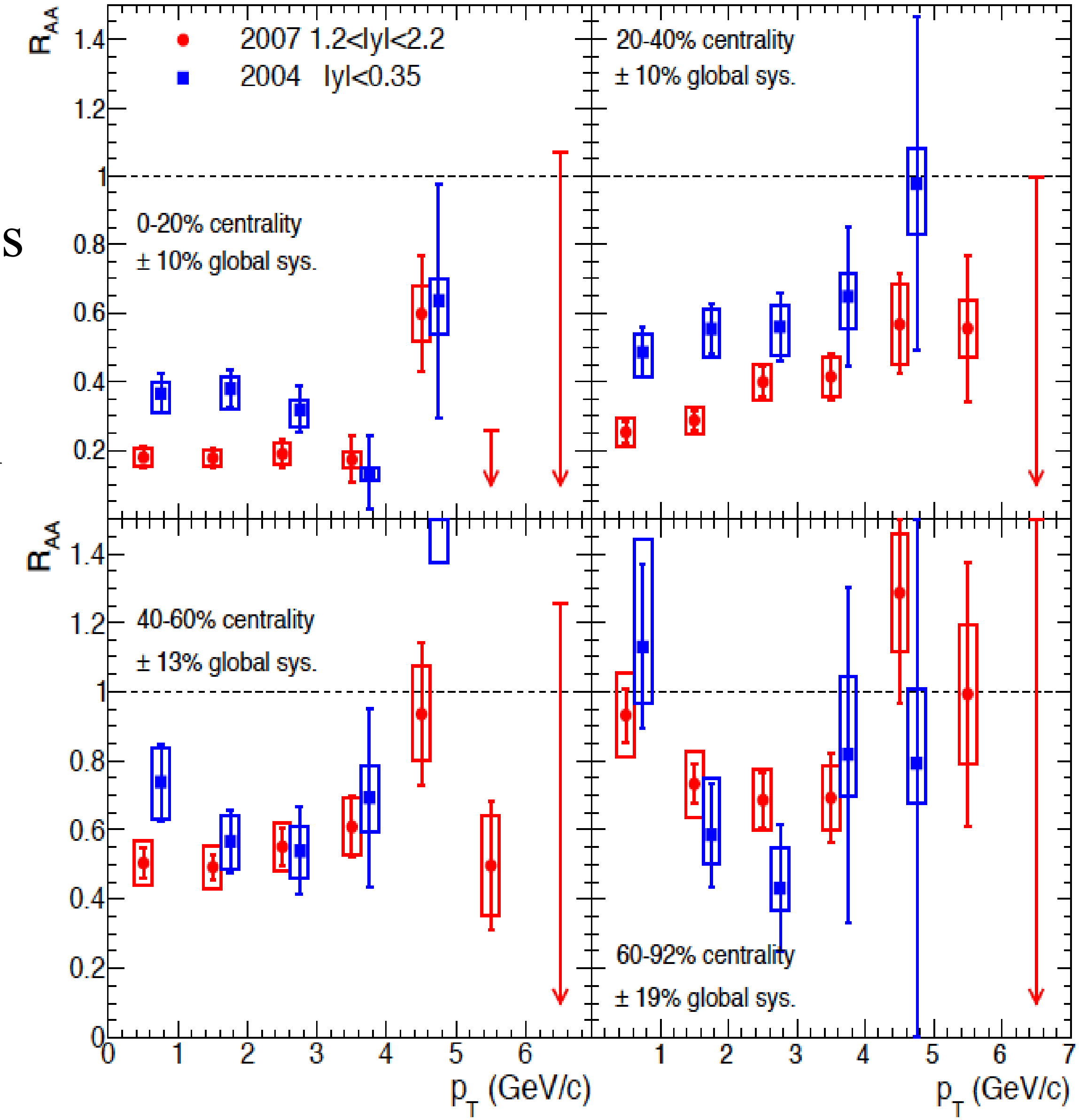
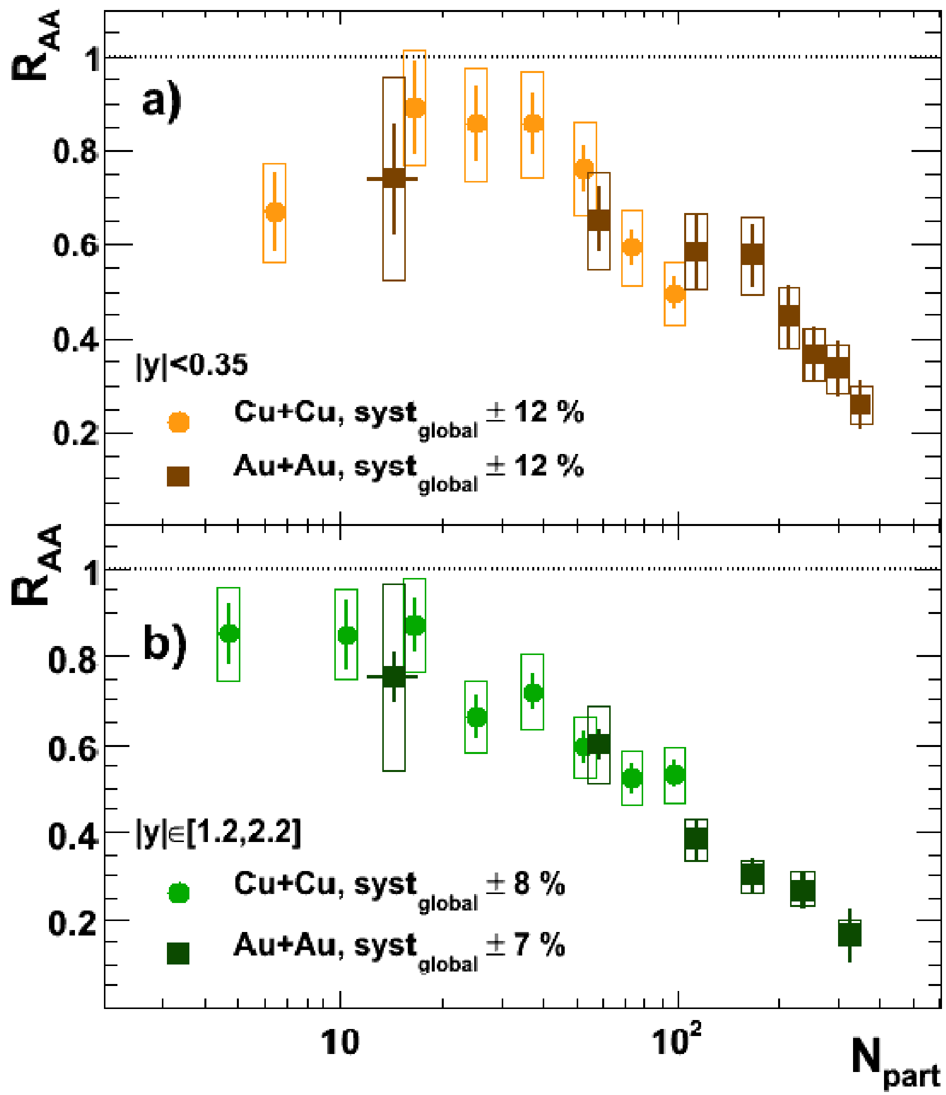


Compare Au+Au and Cu+Cu J/ψ - R_{AA} vs centrality

The **Au+Au** data shown here are from the 2004 RHIC run (PRL 98, 232301 (2007)).

The **Cu+Cu** data are from the 2005 run (PRL 101, 122301 (2008))

They are in good agreement about th **dependence of suppression on N_{par}**



The transverse area is similar for Au+Au and Cu+Cu at the same N_{part} - so not very surprising.

But the Cu+Cu data define the behavior for smaller N_{part} better, due smaller statistical and systematic uncertainties.

We have R_{AA} for Au+Au and Cu+Cu – now what?

We see very strong suppression in central Au+Au collisions. However it is stronger at forward rapidity than at mid rapidity.

Really?

To answer that, we need to understand what processes other than hot matter effects are present in A+A collisions.

We need to consider cold nuclear matter (CNM) effects – effects that modify J/ψ production **in a nuclear target**.

Cold nuclear matter effects

Cold nuclear matter (CNM) effects refer to the modification of the initial J/ψ population due to its production in a nuclear target.

CNM effects include

- Gluon shadowing – modified parton distributions
- Breakup of the precursor J/ψ by collisions with nucleons during the nuclear crossing
- Initial state energy loss of partons
- Cronin effect – multiple elastic scattering of partons

Notes:

- Gluon shadowing affects the underlying charm yield.
- Breakup reduces the **fraction** of charm forming bound charmonium.
- Initial state energy loss changes the rapidity distribution
- Cronin effect modifies the p_T distribution.

A note on time scales in nuclear collisions (RHIC)

At 100 GeV/nucleon (200 GeV/nucleon center of mass) the colliding nuclei have $\boldsymbol{\gamma} = \mathbf{100}$. Time scales are roughly (in the CM):

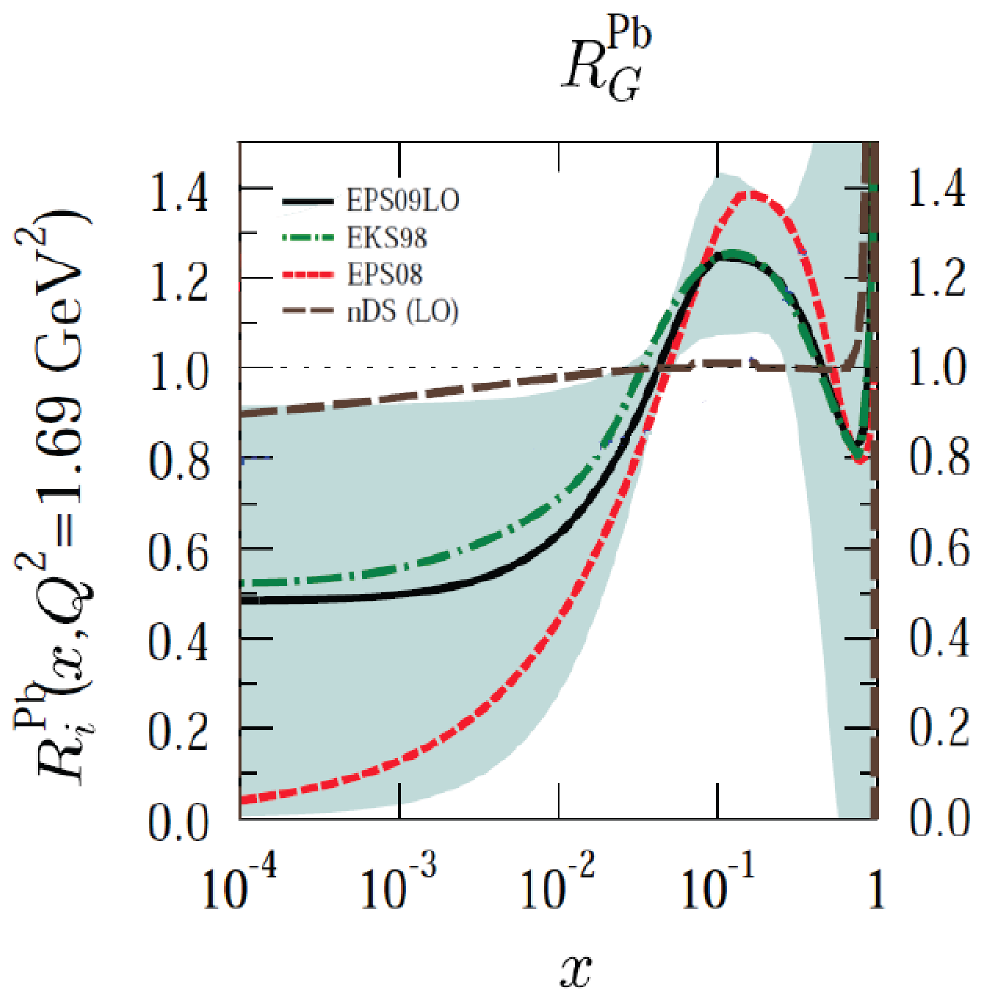
Nuclear crossing time	~ 0.1 fm/c.	⟵ **CNM effects**
J/ψ meson formation time	~ 0.3 fm/c	
QGP thermalization time	~ 0.3 to 0.6 fm/c	
QGP lifetime	~ 5-7 fm/c	
J/ψ lifetime (free space)	~ 2000 fm/c	

The creation of the charm pair that evolves into the J/ψ and its modification in the **hot** medium occur on different time scales. They are often taken as being factorizable.

If so, we can study the cold nuclear matter (CNM) effects using p+A to help understand the initial J/ψ population in A+A.

Shadowing

Modification of quarkonia production in nuclear targets is seen in Deep Inelastic Scattering data, and is referred to as “shadowing”. DIS data have been fitted to extract nuclear modified **Parton Distribution Functions** (nPDF's) vs **Bjorken x** of the target parton and $\mathbf{Q^2}$ of the hard interaction.



Parameter sets in use include:

- EPS09 [JHEP 04, 065 (2009)]
- nDSg [PRD 69, 074028(2004)]
- EKS98 [EPJ C9, 61 (1999)]

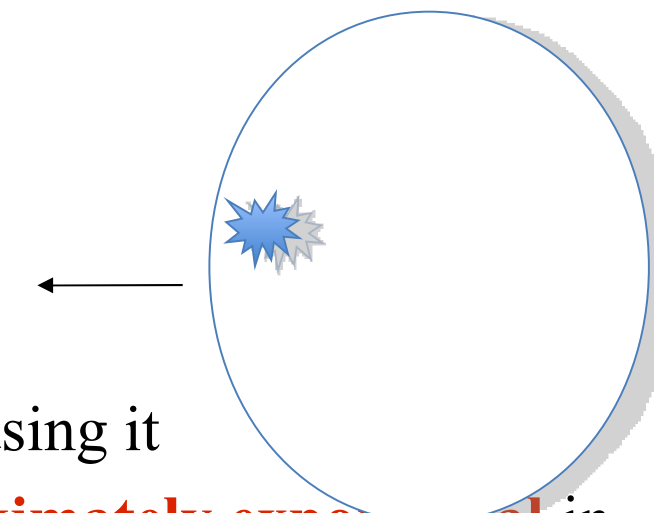
We are interested in the **gluon** Modification, since quarkonia production at high energy is dominated by gluon diagrams.

Breakup

After a **bound** charm pair is produced in the Au nucleus, it can be broken up by a collision with a nucleon that passes through the production point later.

Account for this loss using a cross section, σ_{br}. In general, σ_{br} depends on $\sqrt{s_{NN}}$ and rapidity – not much theoretical guidance!

It also depends on **which state** (J/ψ, ψ', χ_c), so when we use one value of σ_{br} we are mocking up the breakup of all states that result in a J/ψ.



And, of course, if we **fit** σ_{br} to data, we are using it to mock up **any** physics effect that is **approximately exponential** in its dependence on nuclear thickness. So don't take it's physical meaning too seriously.

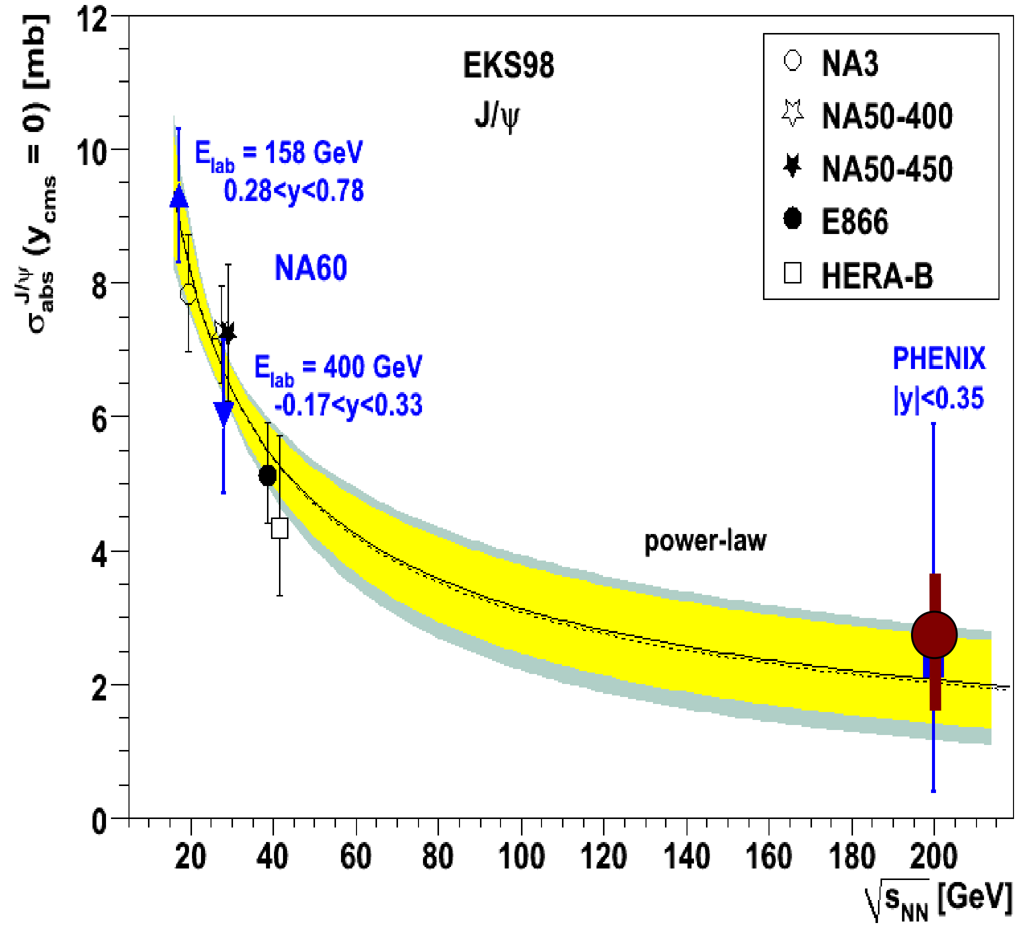
J/ψ breakup cross section energy dependence

Lourenco, Woehri and Vogt made a systematic analysis at **y~0** using EKS98 nPDF's + σ_{br} and saw a clear **collision energy dependence** of σ_{br}.

The PHENIX data point shown here is from the 2003 d+Au run.

Add a PHENIX point from the 2008 run (2.7 +1.1 -1.2 mb) (from fit by ADF using EKS98 calculations from Ramona Vogt, see later).

JHEP 0902:014 (2009)



σ_{br} may depend on rapidity (and p_T?) also.

Initial state energy loss

Partons in the projectile interact with partons in the target prior to the hard collision that produces the J/ψ.

This results in a rapidity shift for the produced J/ψ that is expected to look like suppression at forward rapidity.

The magnitude of the effect does not seem to be well established.

Cronin effect

Refers to broadening of the p_T spectrum in collisions with nuclei.

Presumed to be due to multiple inelastic scattering of the incoming parton before it interacts in the hard process that produces the J/ψ.

Vectorially adds p_T to the produced J/ψ, reducing the yield at low p_T and increasing it at higher p_T (~ 5-10 GeV/c).

Again, the magnitude seems to be not well established.

d+Au data

One can study CNM effects in p+A collisions. In fact at RHIC we use d+A collisions because the **low magnetic rigidity** of the proton would require physical adjustments of magnet positions in RHIC. Possible, but requires a **dedicated p+A run**.

Nuclear effects on partons in the deuteron are known to be very small from E866 data, so we consider a deuteron to be a separate proton and neutron.

The PHENIX BBC **trigger efficiency** is 88% for d+Au collisions.

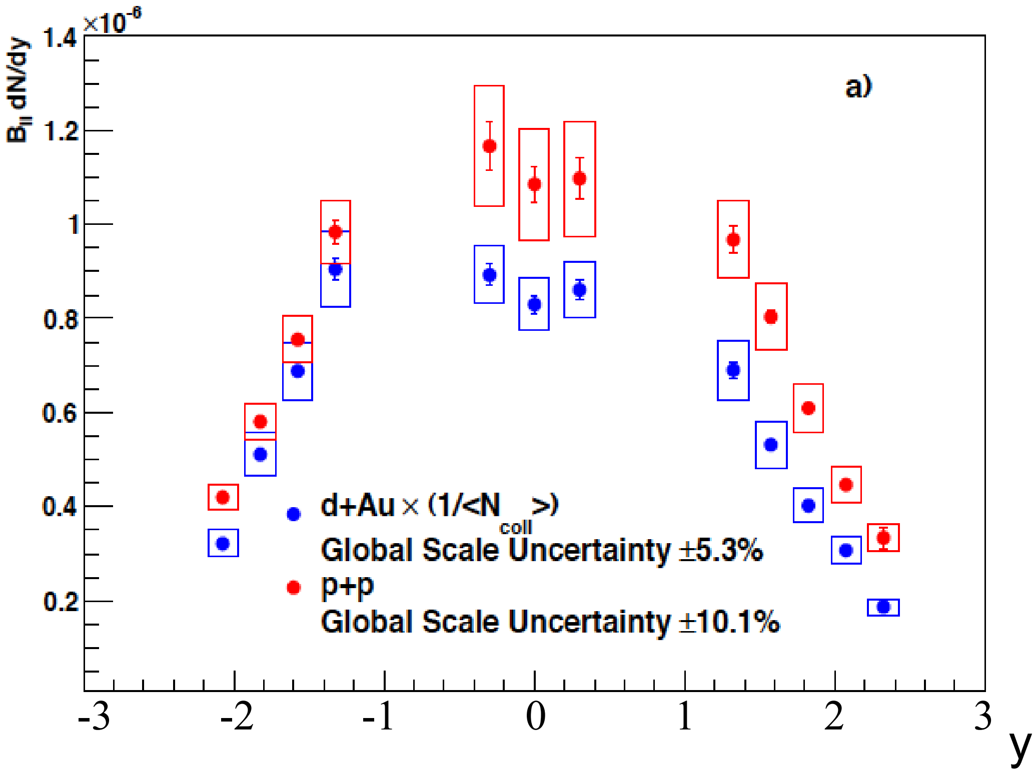
We measure **centrality** in d+Au collisions using the signal from the BBC counter in the Au-going direction. We use four centrality bins (0-20%, 20-40%, 40-60% and 60-88%).

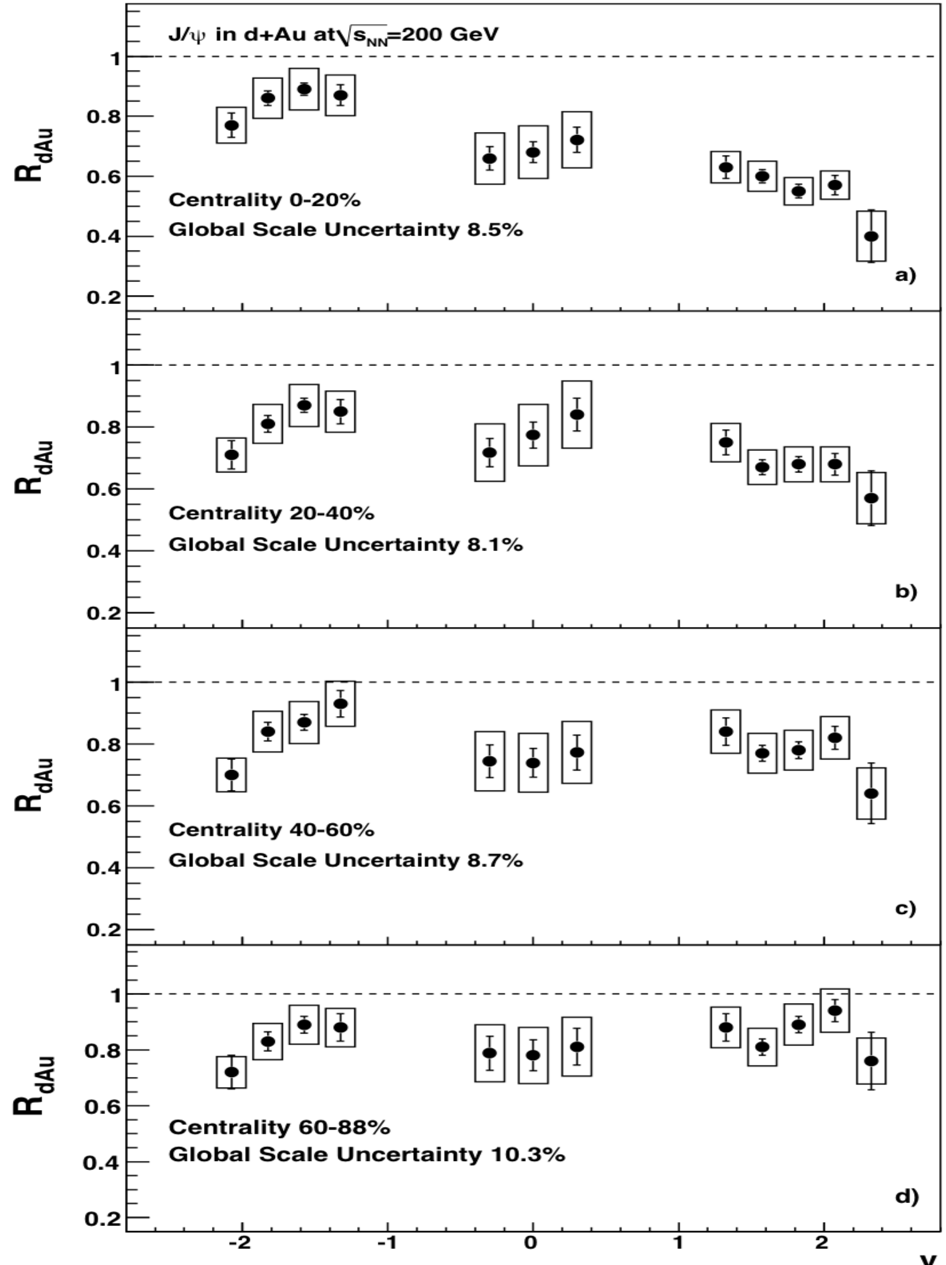
We estimate $\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$ values for our centrality bins from a Glauber calculation, as we did for Au+Au.

PHENIX run 8 d+Au rapidity dependence

PHENIX d+Au J/ψ results from Run 8. R_{dAu} in **four centrality bins**, at **12 rapidities** from -2.075 to + 2.325.

The three rapidity bins near y=0 are measured with electrons in the central arms. The other 9 rapidity bins are measured in the muon arms.





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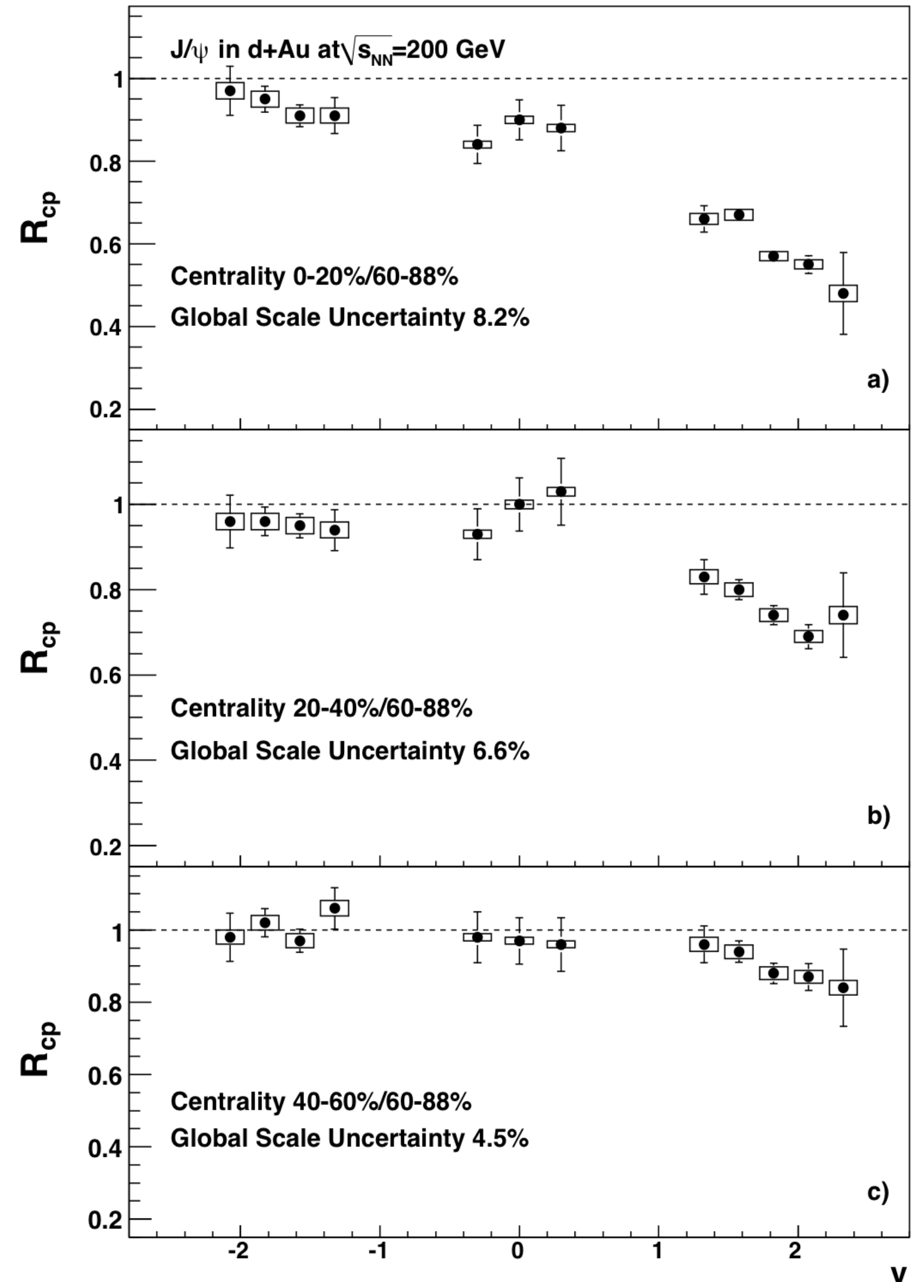
R_{CP} for d+Au vs rapidity

We define the ratio of central to peripheral R_{dAu} as R_{CP} :

$$R_{CP} = \frac{R_{dAu}(0-20)}{R_{dAu}(60-88)}$$

Taking the ratio R_{CP} cancels out many systematic uncertainties, at the expense of the loss of the peripheral bin modification.

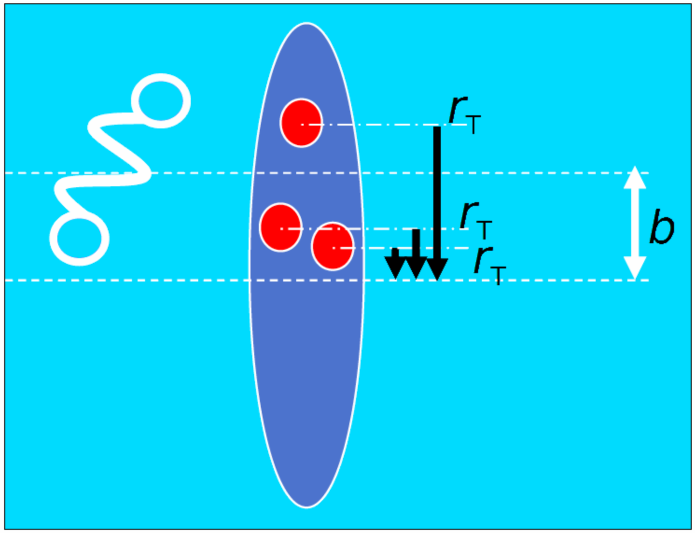
Later, we see that the **combination** of R_{dAu} and R_{CP} is powerful.

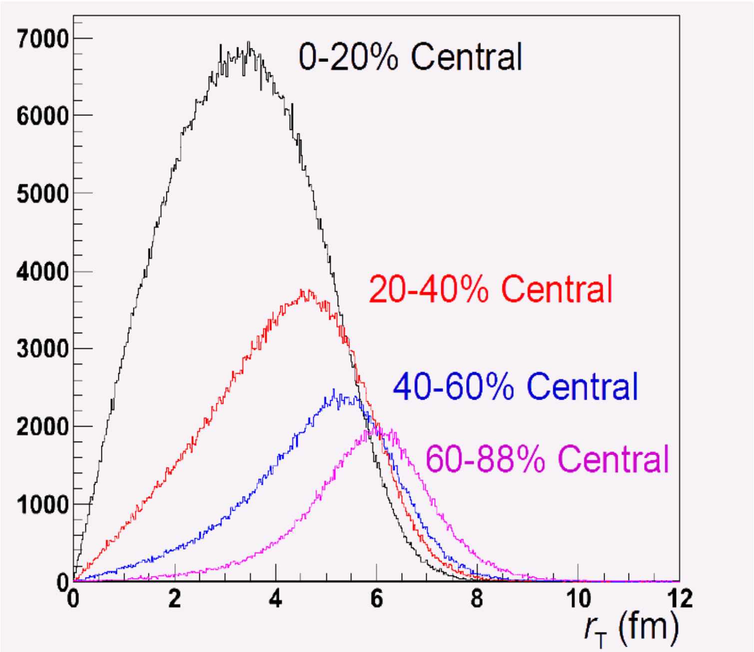


What can we learn from the d+Au data?

To try to understand the d+Au data we started with a very simple exercise to see if the **data can constrain** the behavior of the modification as the **impact parameter of the nucleon** in the Au nucleus changes.

We need to discuss how to add a theoretical modification to a Glauber model of d+Au collisions, so we can compare the results with data.



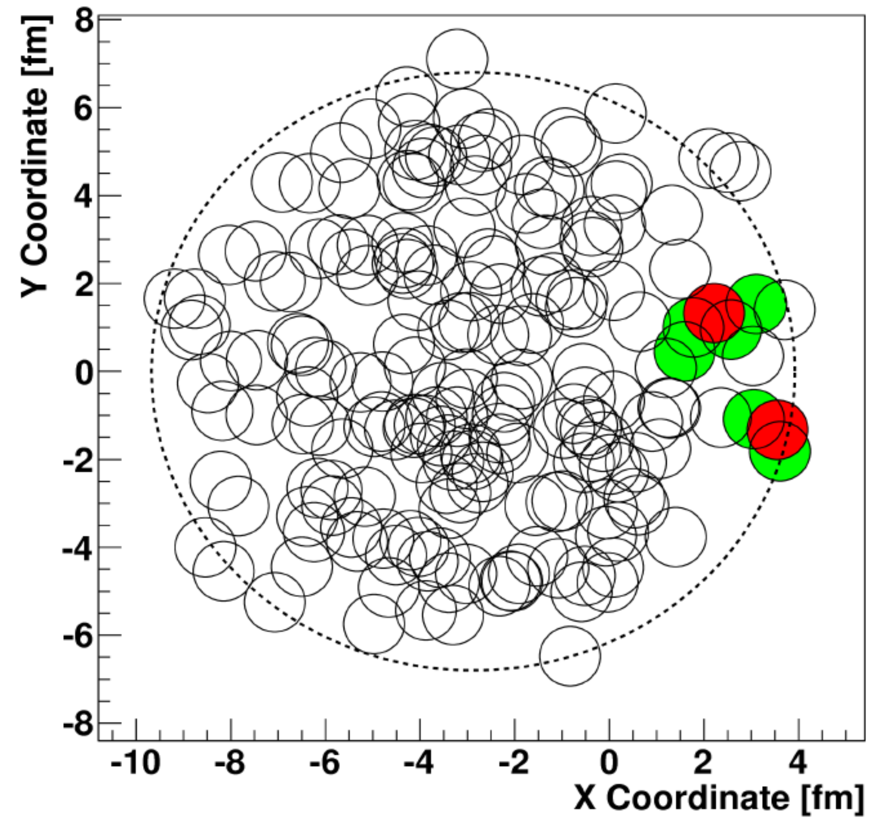


Glauber Model of d+Au collision

We use a **Glauber model** to convert model parameters into a prediction of the resulting data.

Each collision is characterized by a "snapshot" in transverse space of where the nucleons are, based on:

- A Woods-Saxon density distribution
- A realistic impact parameter distribution



The figure shows an example of a d+Au peripheral event. The red circles are the deuteron nucleons, the green circles are "struck" Au nucleons.

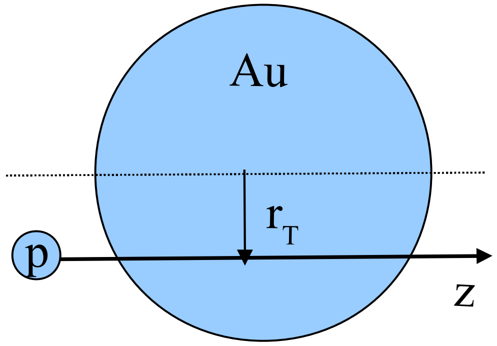
Theoretical modifications are applied to each nucleon-Au collision individually on an **event by event** basis in the Glauber calculation, and the modification averaged over centrality bins to calculate the predicted R_{dAu}.

Define nuclear thickness Λ

We need to define the longitudinal density integrated nuclear thickness in Au at **impact parameter r_T**. It has units fm^{-2}:

$$\Lambda(r_T) = \int dz\, \rho(z, r_T)$$

Where z is the longitudinal distance in the projectile direction and $\rho(z,r_T)$ is the nuclear density at z and r_T, obtained from a Woods Saxon distribution.

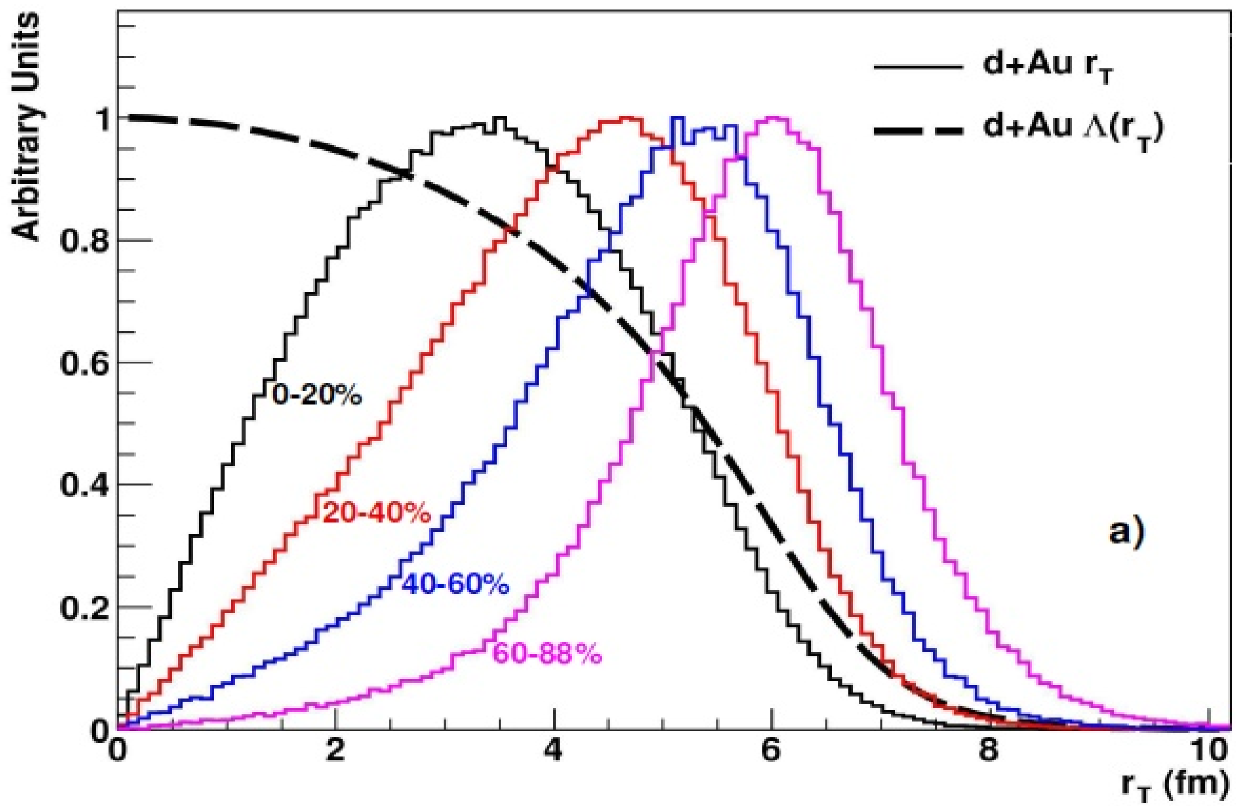


To calculate the effect of σ_{br}, **start the integral** at the production point z_1 of the J/ψ precursor.

Centrality bins

The centrality bins are **highly overlapping.** This is the nucleon-Au impact parameter (r_T) distribution from the Glauber model (normalized to unity for each centrality bin, to make comparison easier)

This just reflects the statistical fluctuations in the BBC detector signal for a given impact parameter.



A surprising result

R_{dAu} (0-100) **vs** R_{CP} (0-20/60-98)
(= **overall modification** vs **slope**)

Data compared with some simple **mathematical** forms for the modification vs nuclear thickness, in a Glauber model.

$$M(r_T) = e^{-a\Lambda(r_T)}$$

$$M(r_T) = 1 - a\Lambda(r_T)$$

$$M(r_T) = 1 - a\Lambda(r_T)^2$$

The forward rapidity data points are not consistent with even a pure quadratic thickness dependence.

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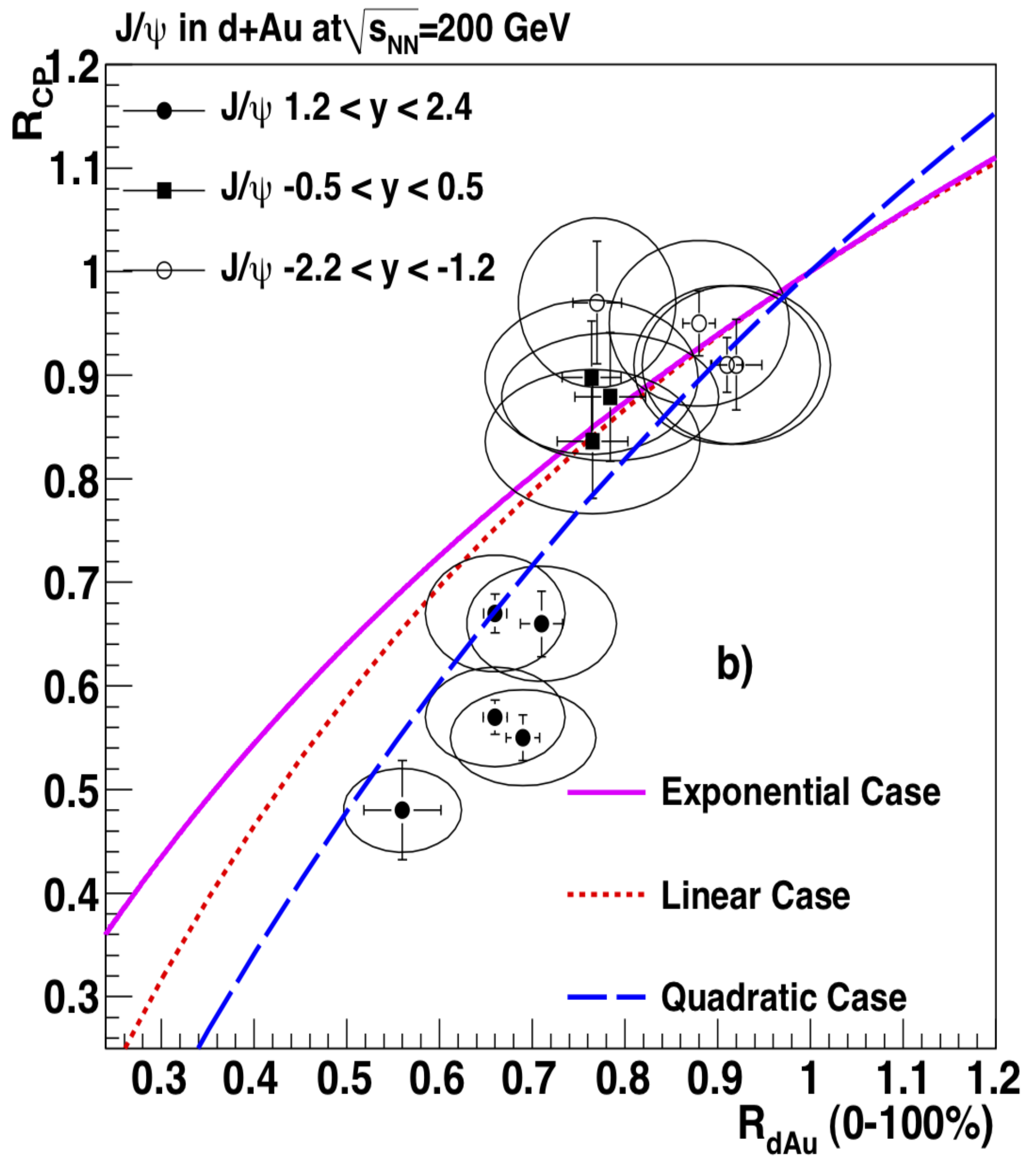


Let's try calculations with physically motivated modifications

See how well one can reproduce the R_{CP} vs R_{dAu} behavior with a Glauber calculation that includes:

- Shadowing with a **linear** or **quadratic** dependence on thickness
- A breakup cross section, σ_{br}, which of course has an inherently exponential dependence on nuclear thickness

What I am about to discuss is taken mostly from the paper:

Nagle, Frawley, Linden Levy, Wysocki, Phys. Rev. C84 (2011) 044911

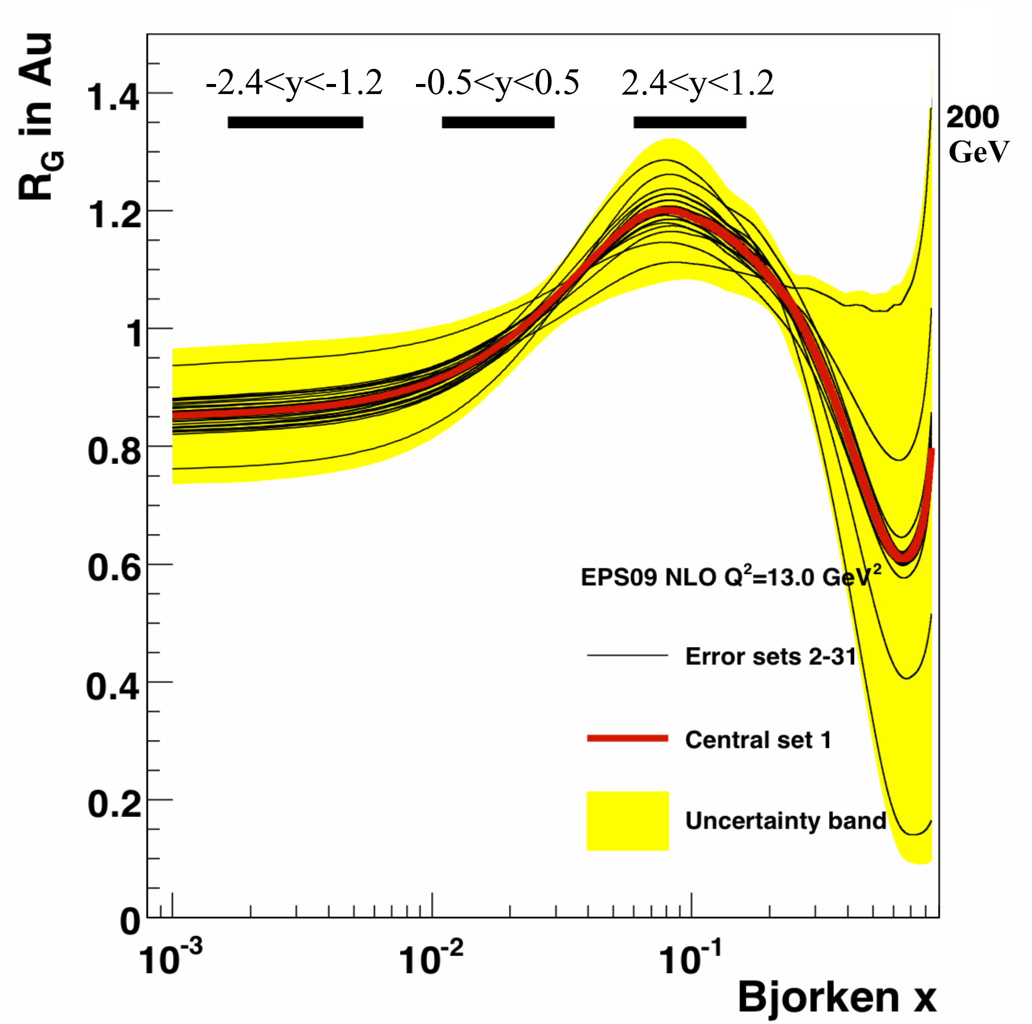
Which contains a detailed description.

Shadowing: R_g for J/ψ production at RHIC

The EPS09 **gluon** modification vs x at $Q^2 = 13$ ($= M^2 + \langle p_T \rangle^2$ for the J/ψ).

It will be important later to know that the input DIS and p+A data have no impact parameter information - **the modification is averaged over the nucleus**.

The approximate **x ranges** sampled by PHENIX at 200 GeV are shown.



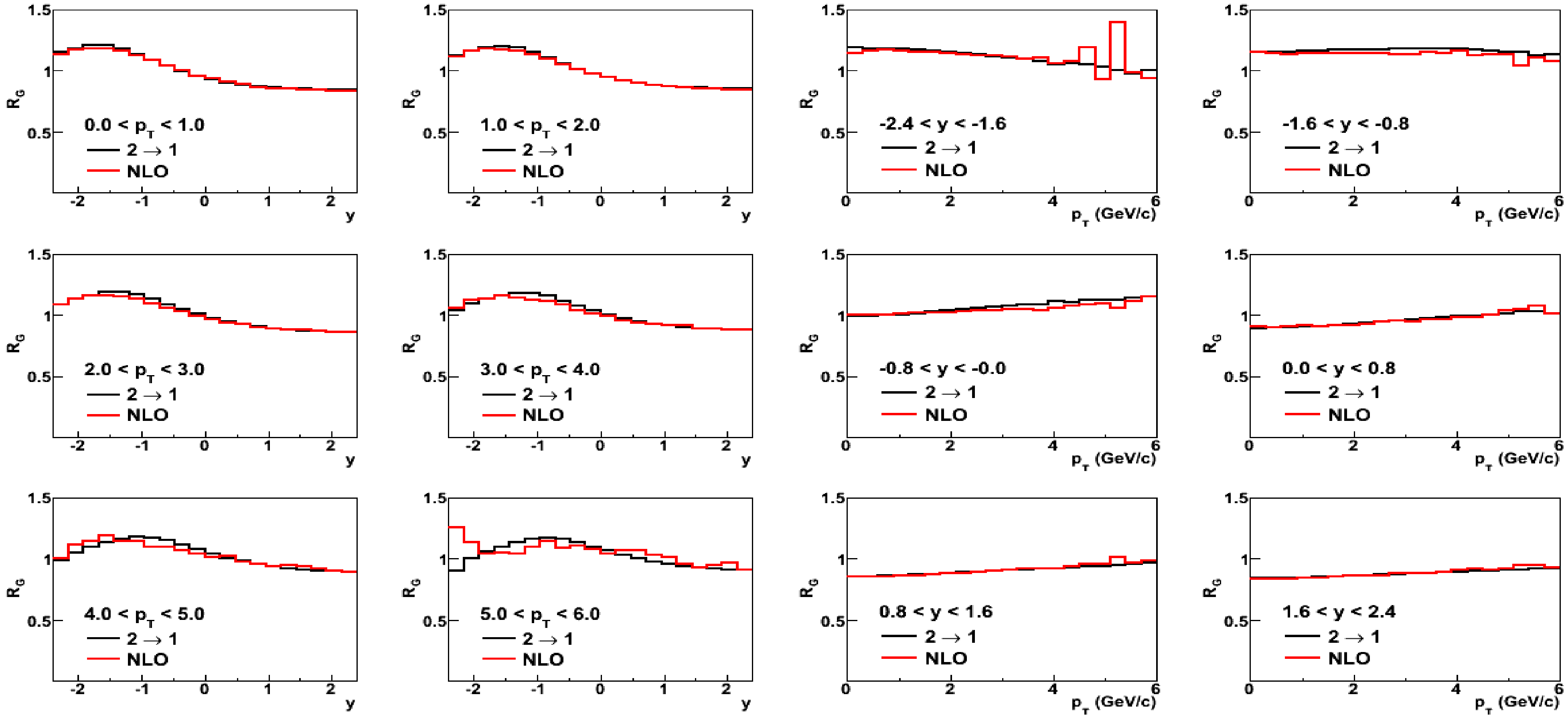
How do we get x_2 and Q^2 for use with EPS09?

We assume **2→1 kinematics**.

$$x_2 = \frac{\sqrt{M_J^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y}$$

Not quite correct - but R_G obtained with x_2 and Q^2 from an NLO calculation by Ramona Vogt is very similar.

$$Q^2 = M_{J/\psi}^2 + p_T^2$$



EPS09 (linear) plus σ_{br}

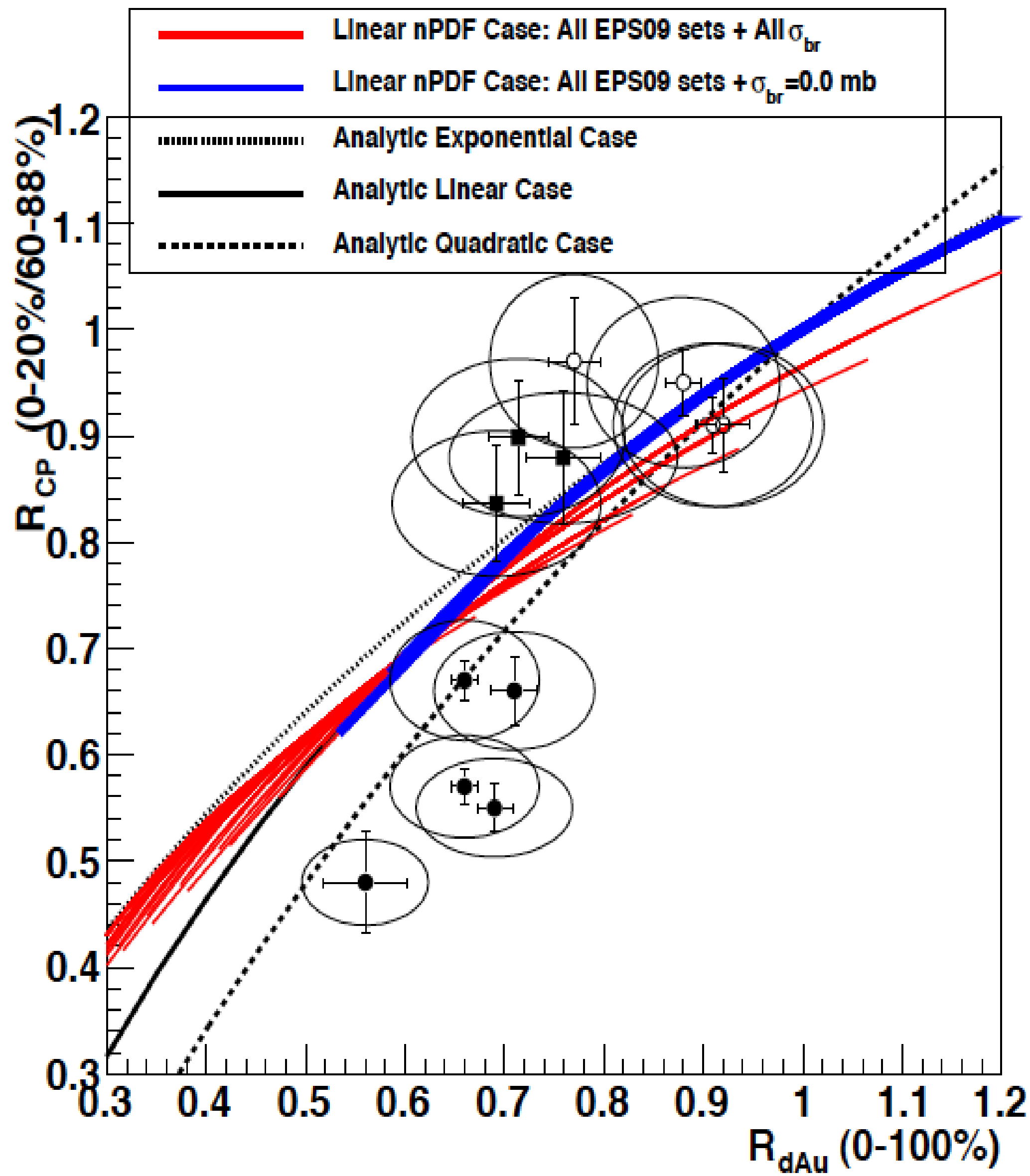
Nagle et al., PRC 84 (2011) 044911

This shows a calculation using EPS09 with a linear thickness dependence plus breakup cross sections varying from **0-20 mb** in 2 mb steps.

$$M_{br}(r_T, z) = e^{-\sigma_{br}\Lambda(r_T, z)}$$

$$M(r_T) = 1 - a\Lambda(r_T)$$

As expected, the linear thickness dependence does not agree with the data at forward rapidity, and the exponential breakup cross section can only worsen things.



EPS09 (quadratic) plus σ_{br}

This shows a calculation using EPS09 with a quadratic thickness dependence plus breakup cross sections varying from **0-20 mb** in 2 mb steps.

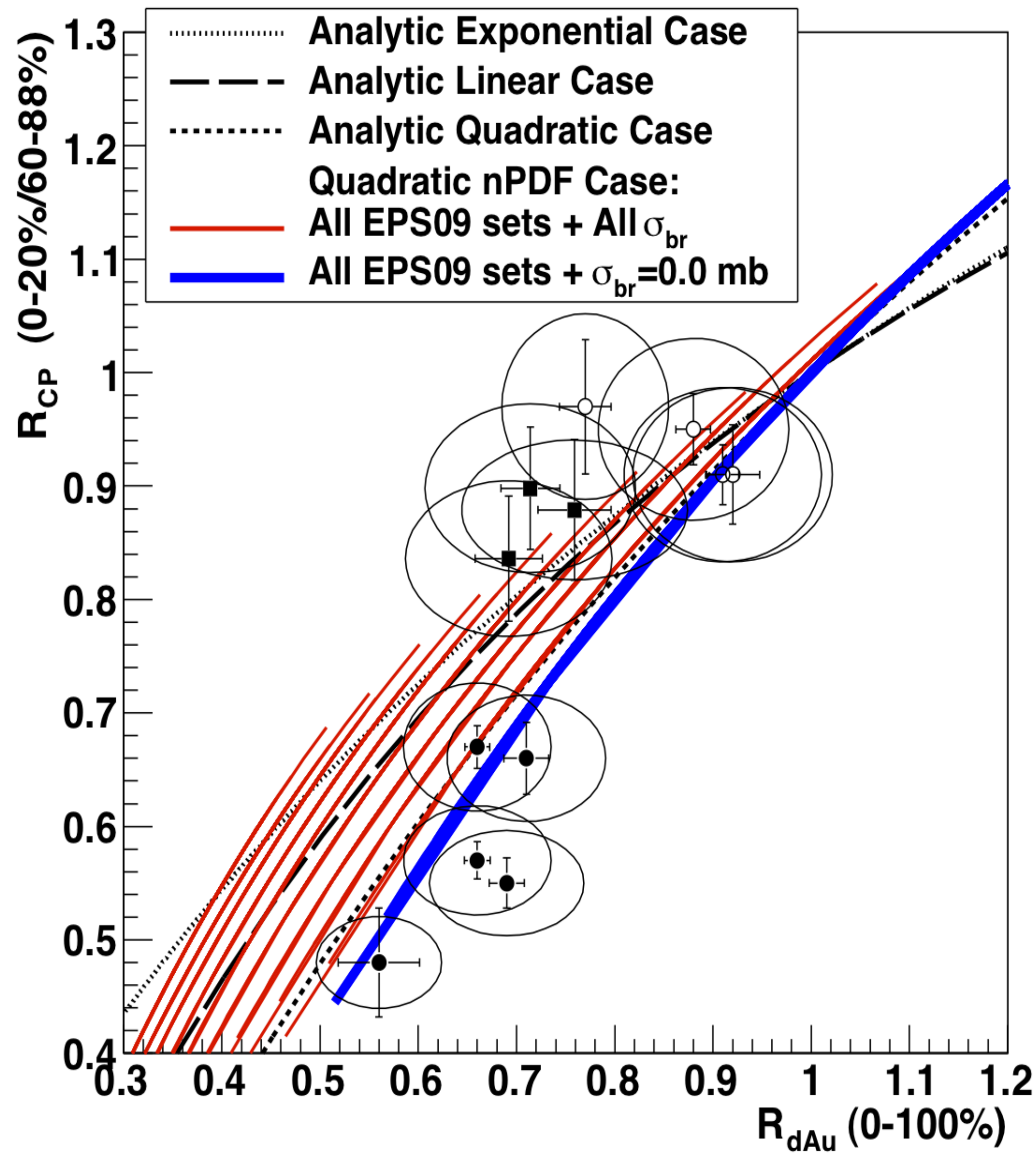
$$M_{br}(r_T, z) = e^{-\sigma_{br}\Lambda(r_T, z)}$$

$$M(r_T) = 1 - a\Lambda(r_T)^2$$

A significant breakup cross section worsens agreement with the data at $y > 1.2$.

Conclusion: We need **at least** quadratic thickness dependence, maybe stronger, at forward rapidity.

Nagle et al., PRC 84 (2011) 044911



How about initial state energy loss?

Can the behavior at forward rapidity be attributed to initial state energy loss?

The key question is whether initial state energy loss can reproduce the nonlinear "turn on" of the modification with increasing centrality.

This was explored in PRC 84, (2011) 044911 by varying the strength, and trying a dependence on path length **L** and also $\mathbf{L^2}$. The calculations did not describe the R_{CP} and R_{dAu} simultaneously.

Some model comparisons

Nagle et al., PRC 84 (2011) 044911

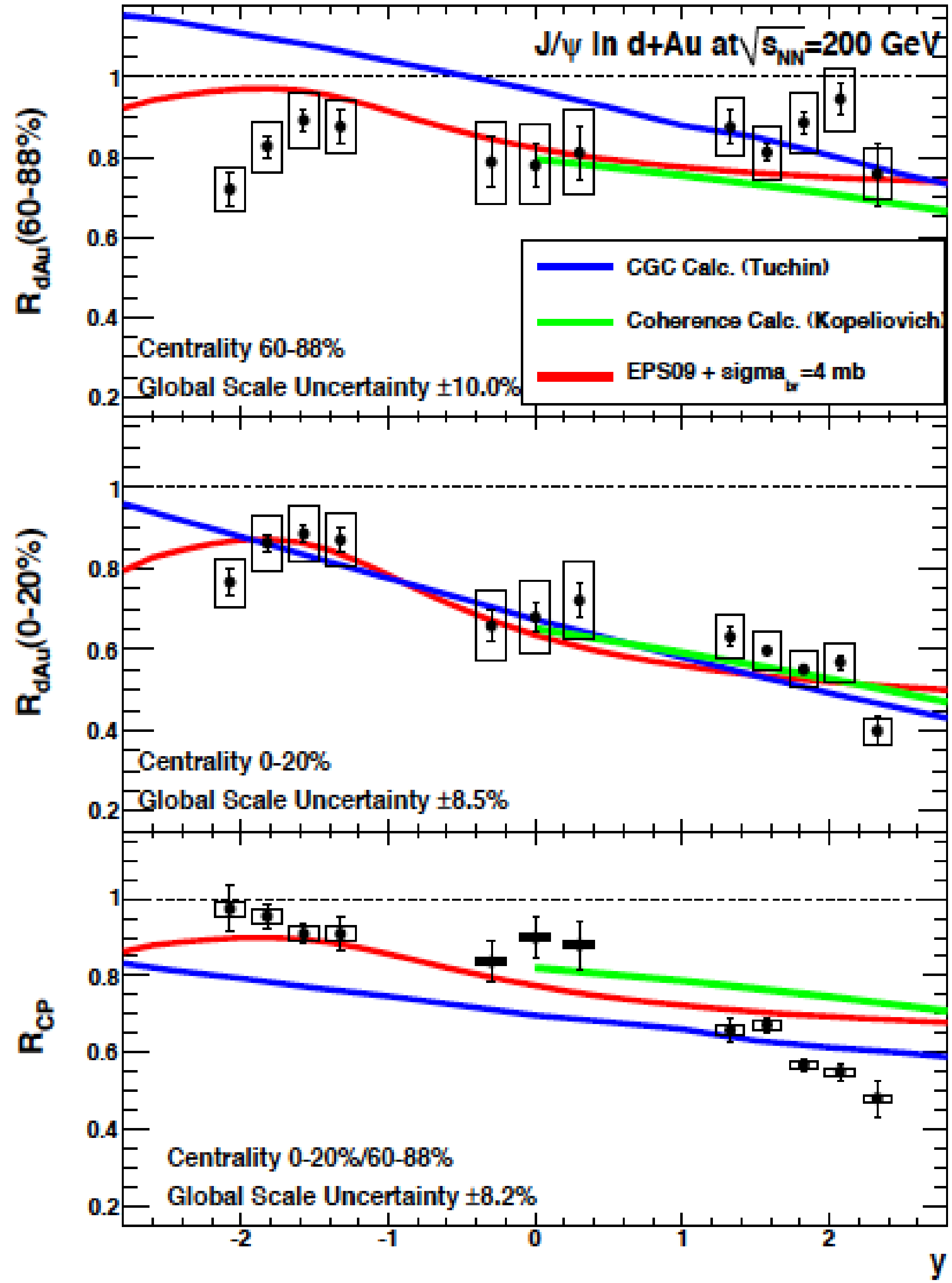
Comparison of the y dependence of the PHENIX data with:

The **red** curves are just EPS09 (linear thickness dependence) plus a constant 4 mb σ_{br}.

The **blue** curves are a CGC calculation from Kirill Tuchin.

The **green** curves represent a model with coherence and color transparency effects (Kopeliovich et al., Phys.Rev. C83 (2011) 014912)

In all three casees the modifications were put into the **same** Glauber calculation.



Transverse momentum dependence

CNM effects can be further constrained by looking at the transverse momentum dependence of R_{dAu}.

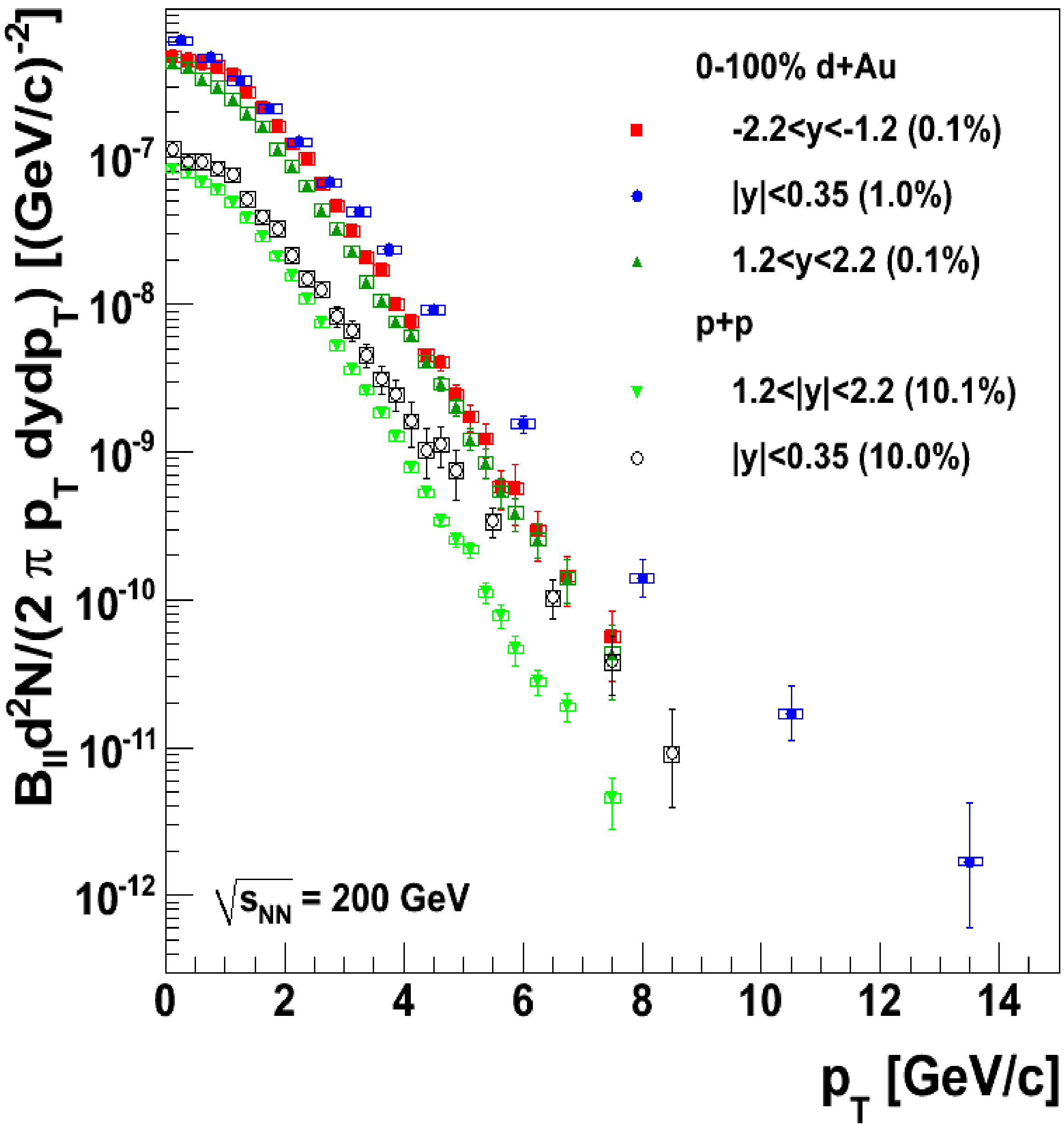
PHENIX very recently published invariant yields and R_{dAu} vs p_T (**arXiv:1204:0777**).

p_T dependence of invariant yields – unbiased (0-100%)

The d+Au data are integrated over all centrality, and corrected to 0-100%.

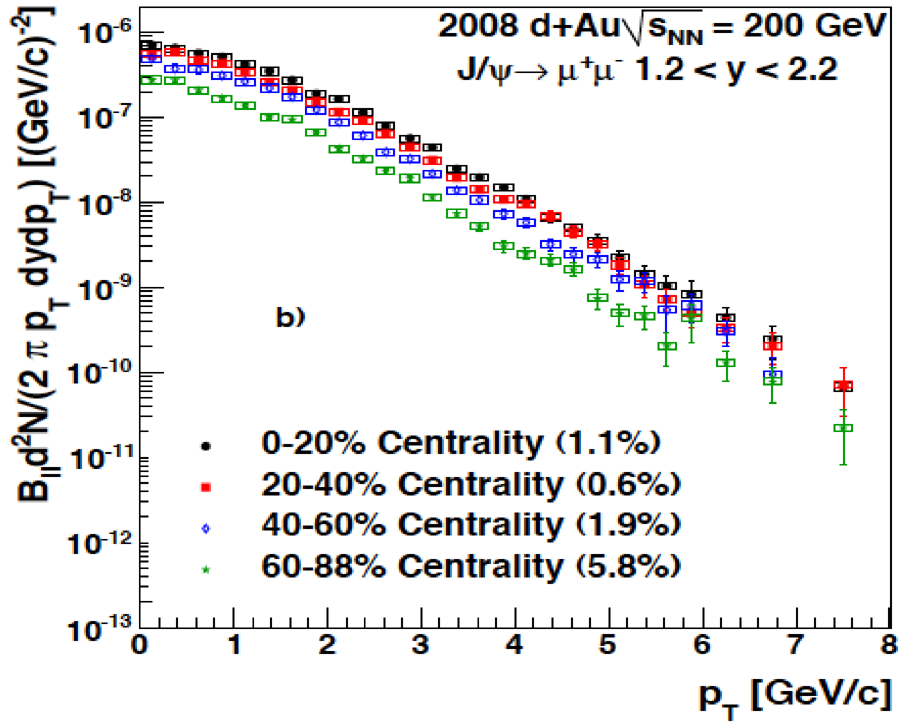
The p+p data are from Run 6 and Run 8.

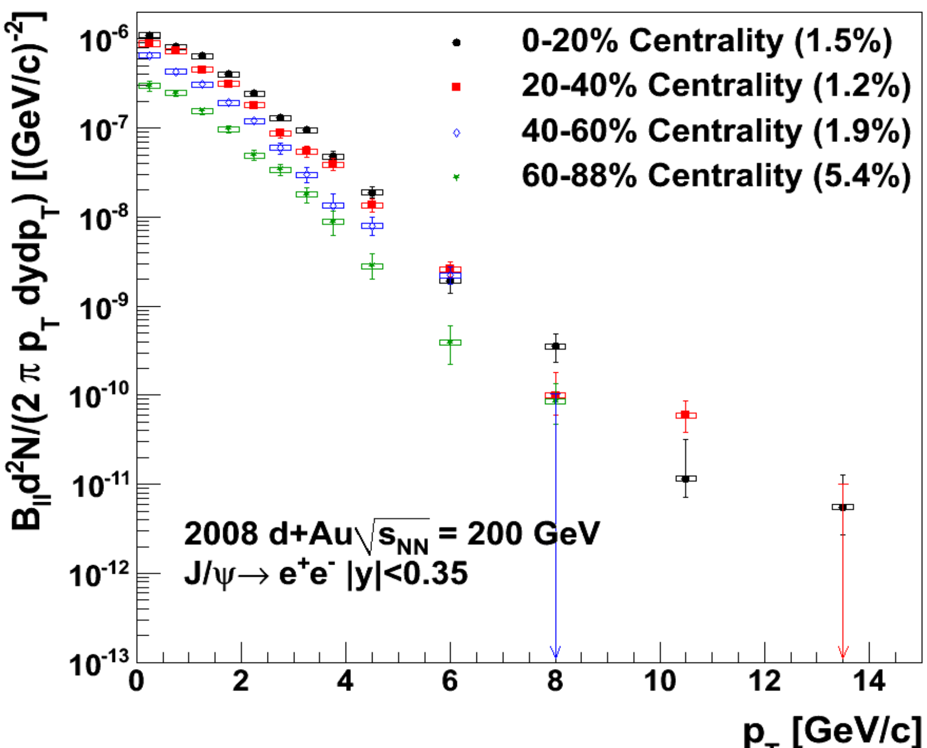
Note: The midrapidity data extend to greater p_T because the better **signal/background** allows smaller yields to be used.

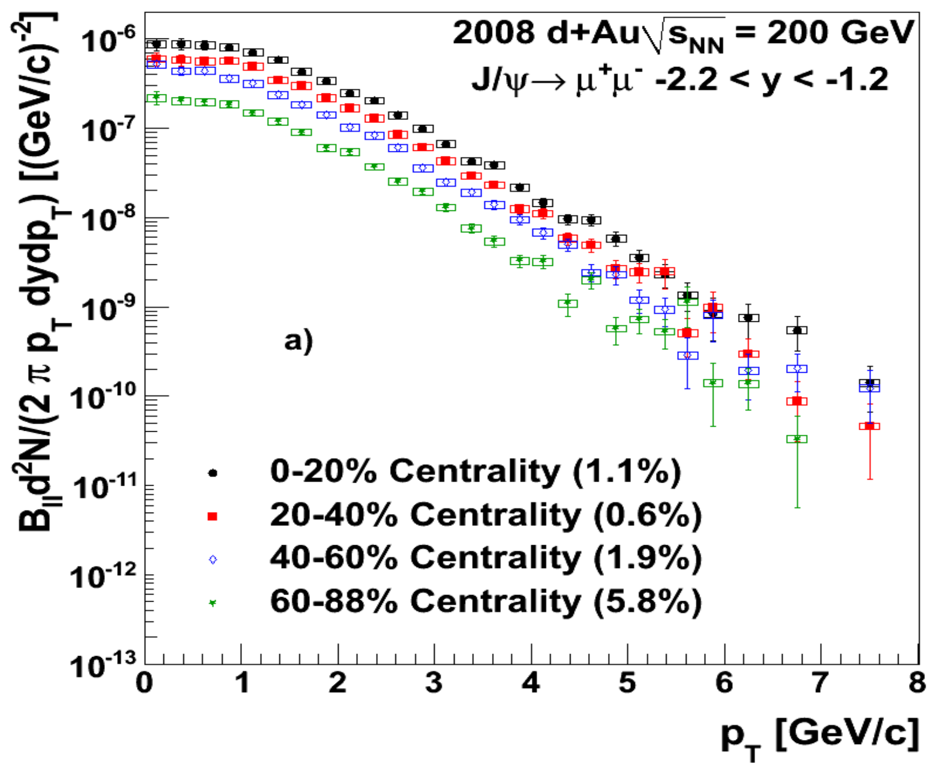


The centrality dependence

The d+Au p_T distributions in four centrality bins (0-20, 20-40, 40-60, 60-88)%.

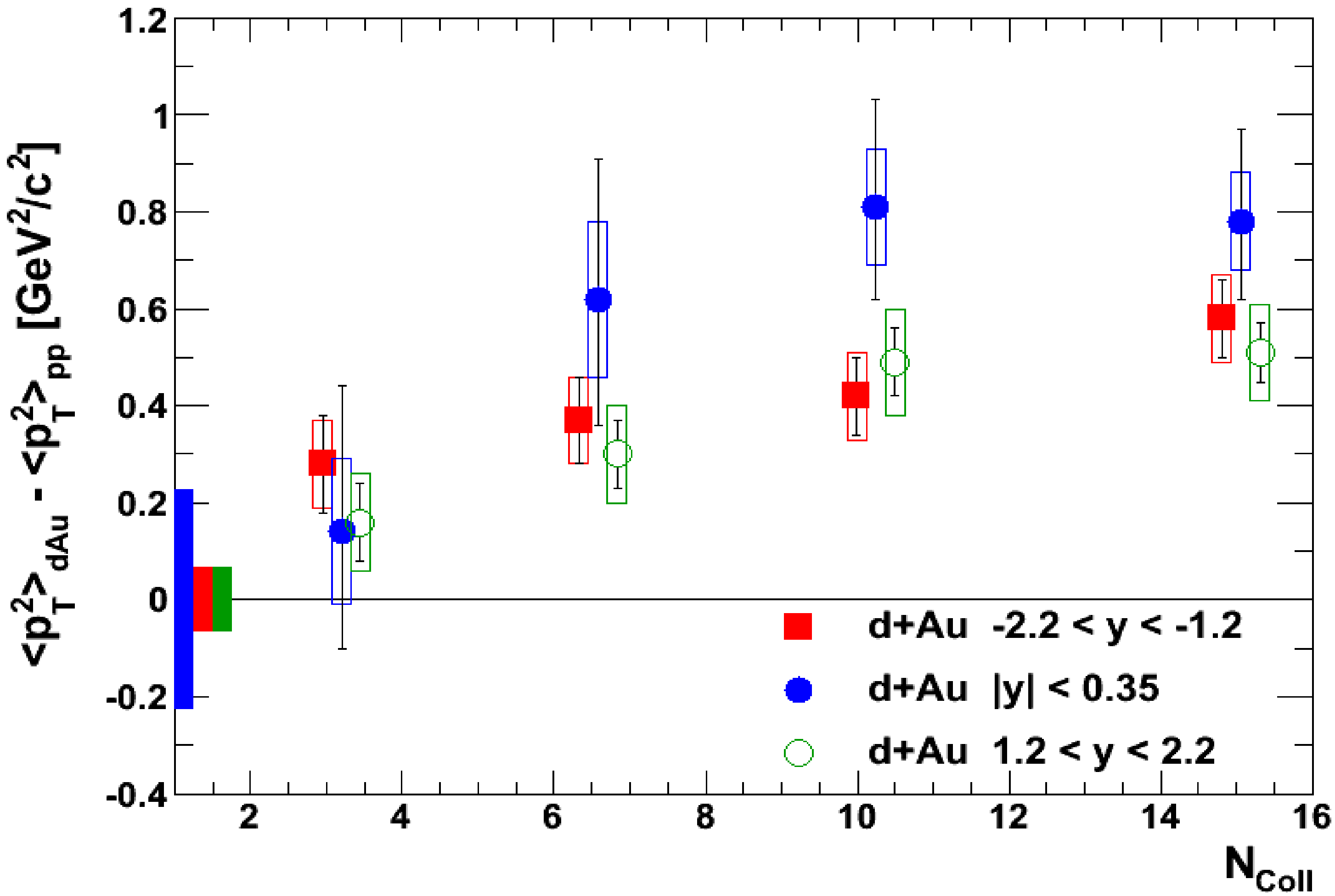






The $<p_T^2>$ increases with collision centrality

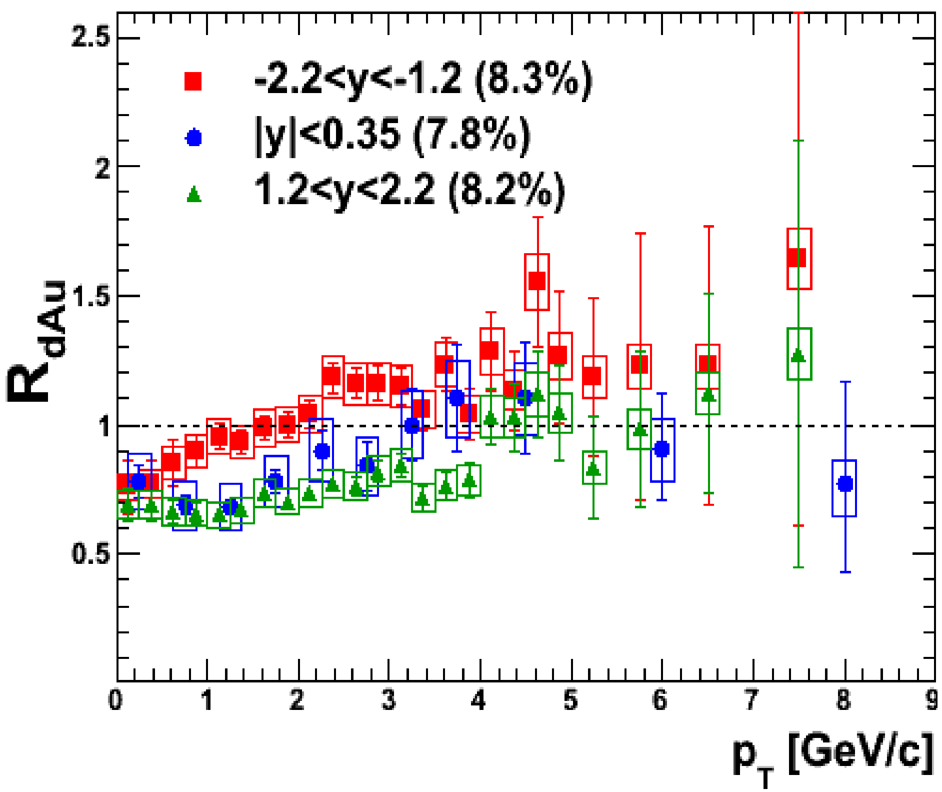
The difference in $<p_T^2>$ values between d+Au and p+p, plotted versus collision centrality, behaves similarly at all three rapidities.
Note: Midrapidity is "harder", so the actual $<p_T^2>$ is larger there too.

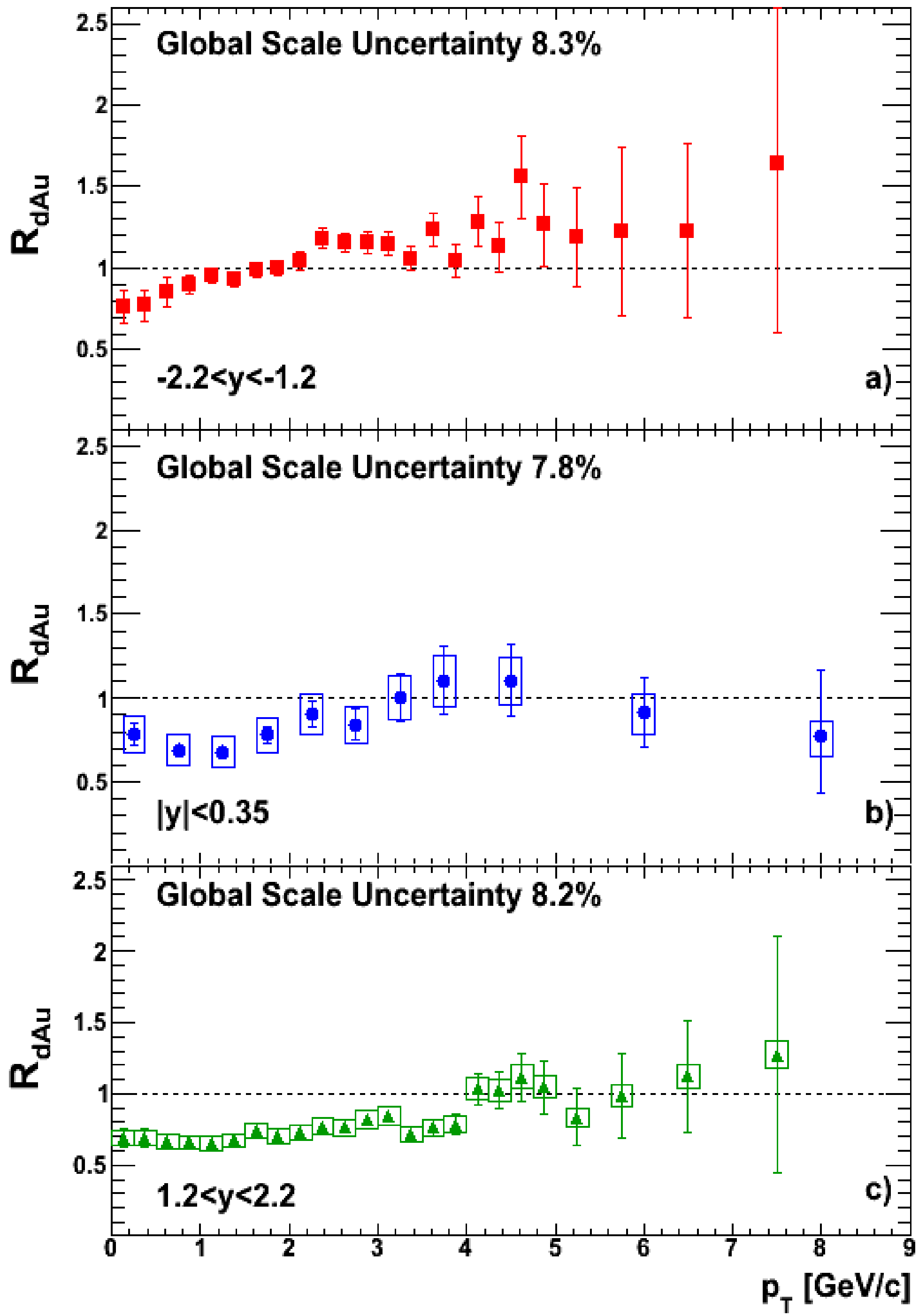


The R_{dAu} for 0-100% unbiased data

Similar behavior at mid (blue) and forward (green) rapidity.

Rather different at backward rapidity (red).





Some model comparisons

Some model calculations are available for comparison with the p_T dependence of R_{dAu}. Consider first:

Lansberg et al. (arXiv:1201.5574, PLB 680, 50 (2009)):
- EKS98, nDSg, or EPS08 with 2→2 kinematics from Color Singlet Model
- Range of σ_{br} = 0, 2.6 4.2 or 6 mb independent of p_T or y
- No added Cronin effect

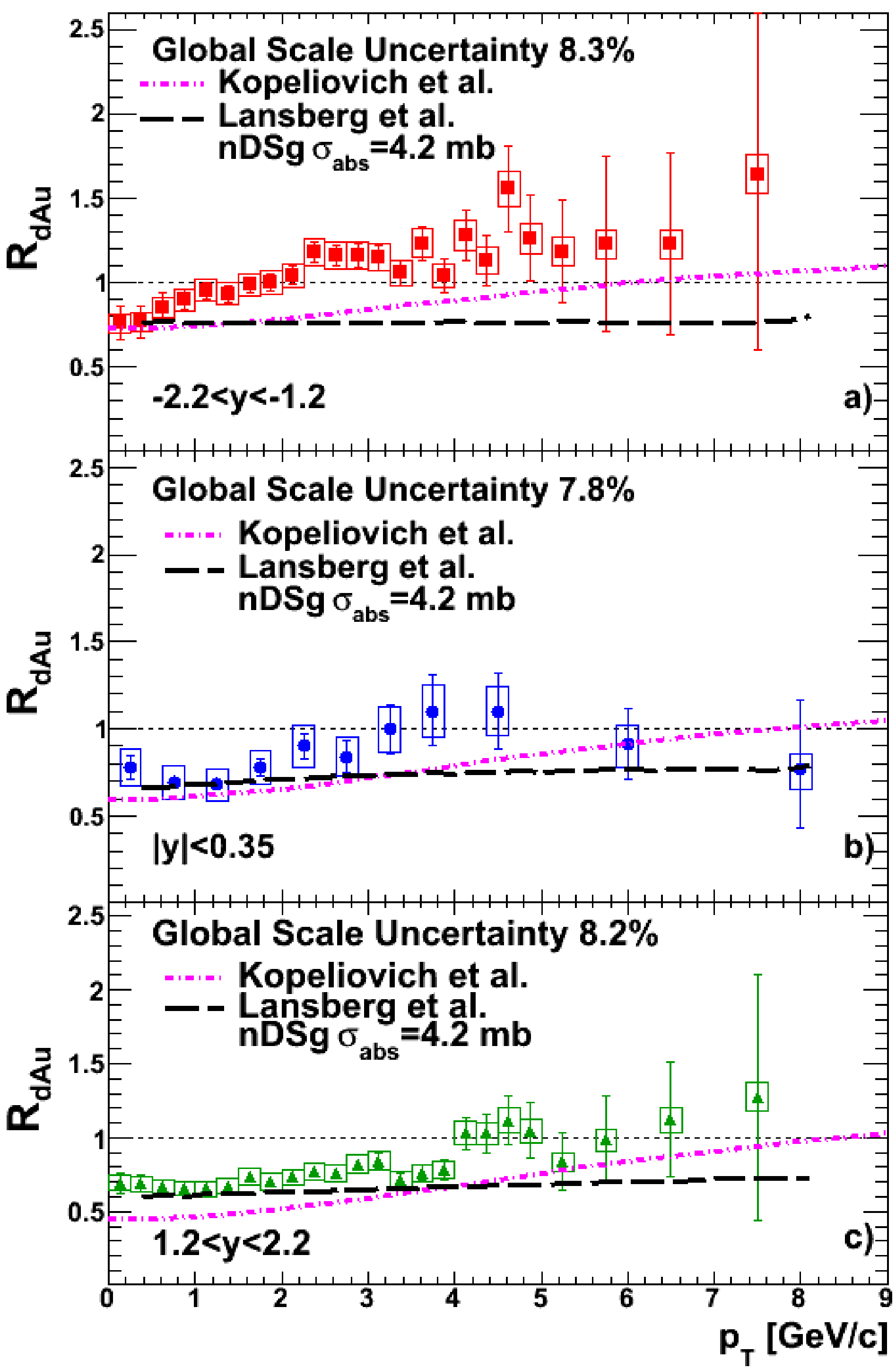
Kopeliovich et al. (NP A 864, 203 (2011), PRC 82, 024901 (2010)):
- nDSg with 2→1 kinematics
- Nuclear breakup from parameterization of color dipole cross section fitted to data – yields **predicted** cross section, dependent on J/ψ kinematics
- Cronin effect is added

Compare to **0-100% unbiased data**.

Kopeliovich et al. reproduce the p_T shape pretty well at mid and forward rapidity, but disagree at backward rapidity and low p_T.

Lansberg et al. (with **nDSg**) agree with data at low p_T at mid and forward rapidity, but is flatter with increasing p_T. At backward rapidity it is like Kopeliovich at low p_T, but then falls instead of rising.

Both use **nDSg for shadowing**. The stronger modulation with p_T of Kopeliovich et al. is presumably due to the added Cronin effect (although an effect from the different kinematics is possible).



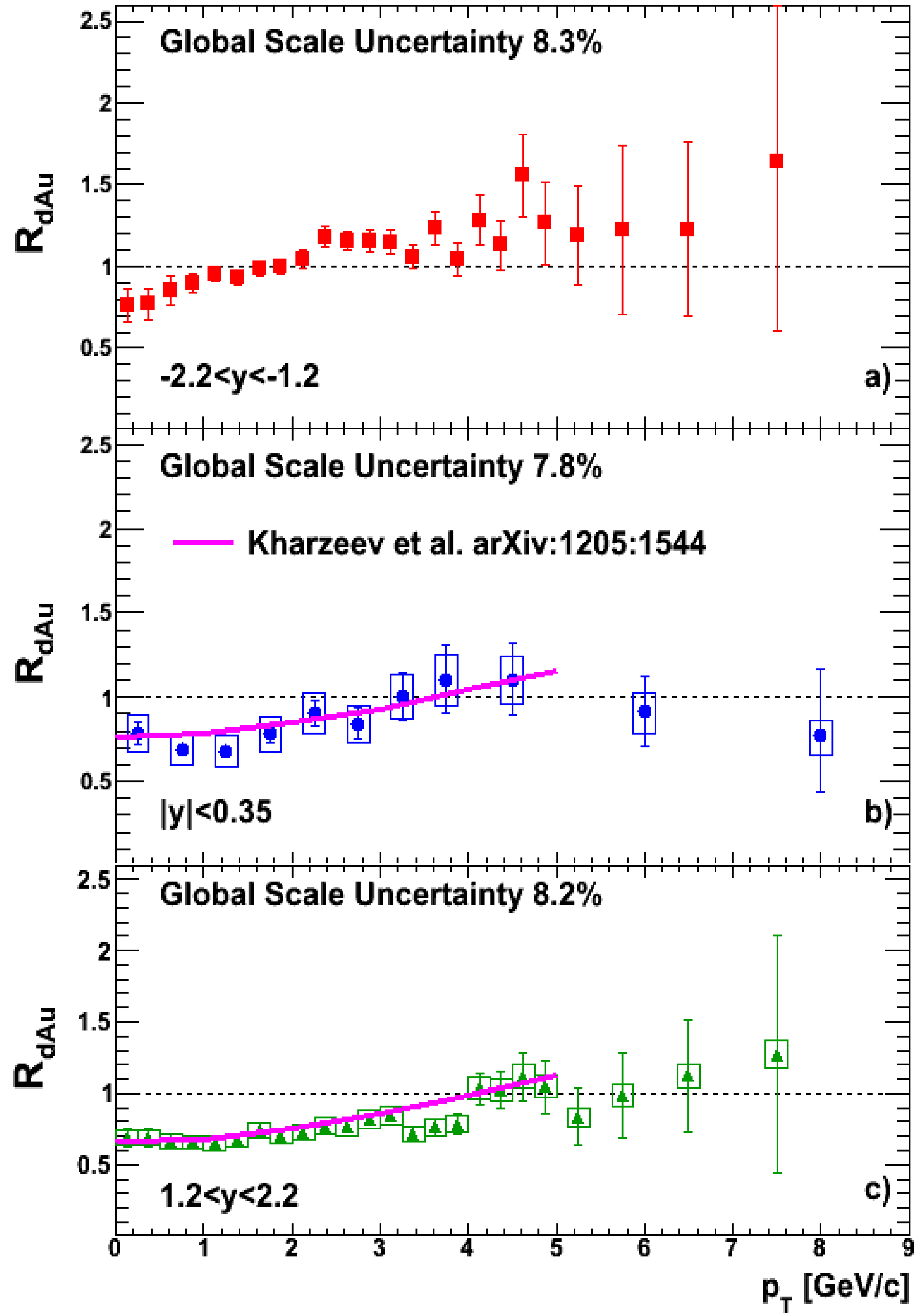
Kharzeev et al., arXiv:1205:1544

After seeing Dima's talk yesterday, where he showed results of his QCD dipole model calculations, I added a comparison of his d+Au calculations to our new **0-100% unbiased data**.

The model does not apply at backward rapidity, should apply at forward rapidity, and is described as "marginally applicable" at mid rapidity at RHIC energies.

Not so bad .....

Centrality dependence?



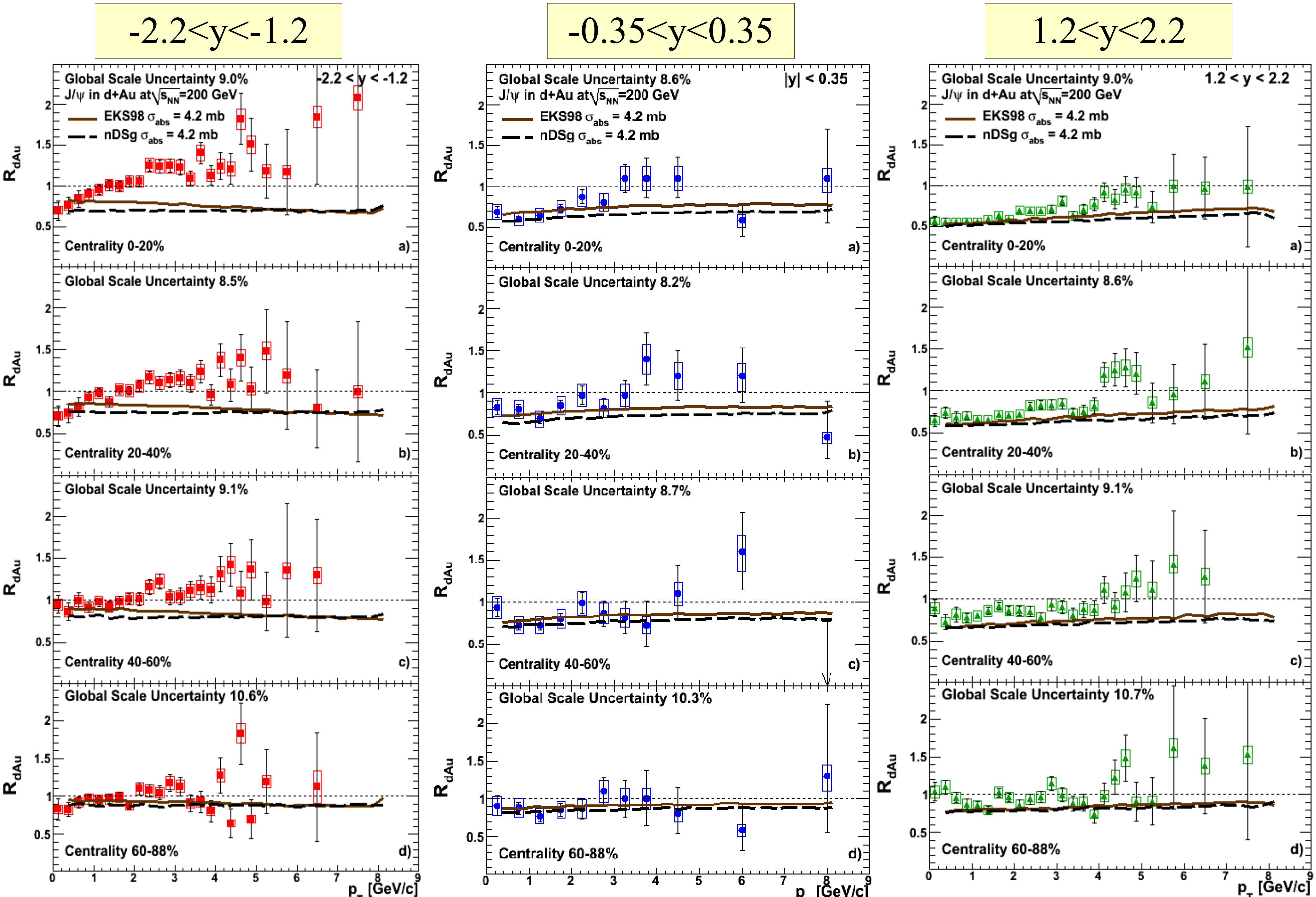
Centrality dependence

Lansberg et al. have calculated the shadowing modification assuming that the spatial dependence of shadowing is **proportional to the local nuclear density**.

Their calculations can be directly compared with PHENIX data in four centrality bins. These are shown for cases with both nDSg and EKS98 parameter sets.

They illustrate the effect of the two different shadowing parameterizations.

Centrality dependence – Lansberg et al.

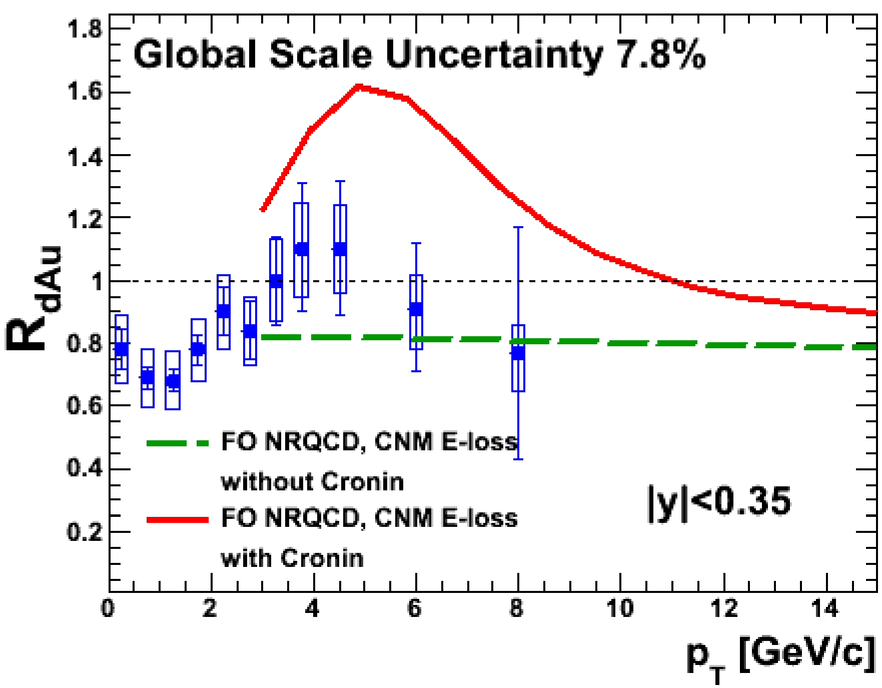


Another model comparison

Sharma and Vitev [arXiv:1203.0329]:

- Nonrelativistic quantum chromodynamics (NRQCD)
- EKS98 for x > 0.25
- Power suppressed coherent final state scattering leads to a modification of parton x
- Initial state energy loss included
- Cronin effect included

The calculation evidently overpredicts the Cronin contribution, although the modulation is at about the same p_T in calculation and data.



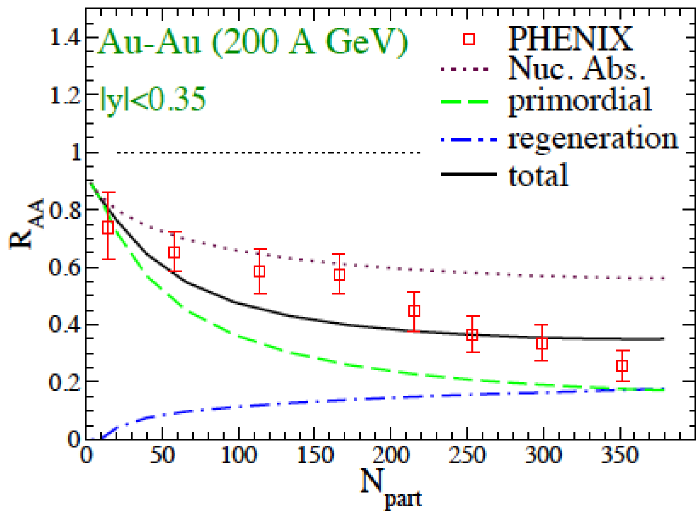
Conclusions about R_{dAu}

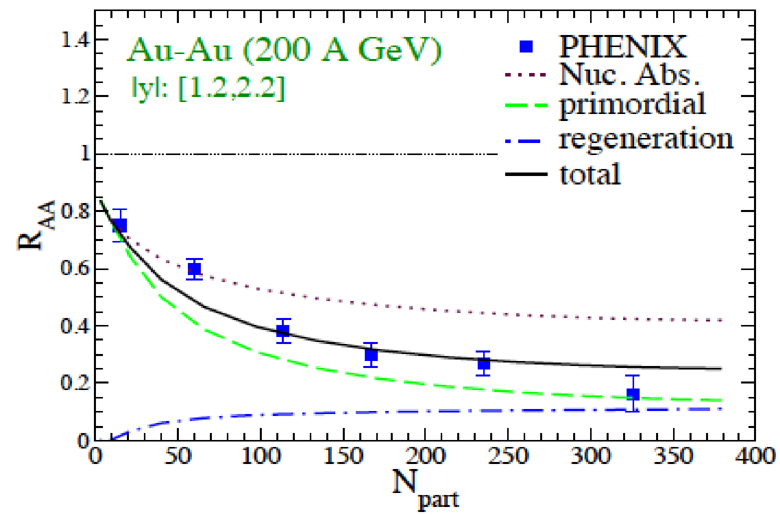
The J/ψ R_{dAu} data require a **shadowing dependence on nuclear thickness** at forward rapidity that is **stronger than linear,** implying that the onset of high density gluon effects occurs suddenly as the impact parameter decreases.

The J/ψ R_{dAu} data set strongly constrains CNM modification vs rapidity and p_T. The **p_T shape** of the backward rapidity data is not described by any of the calculations we have seen, suggesting that there may be issues with the gluon nPDF's at Bjorken x ~ 0.1.

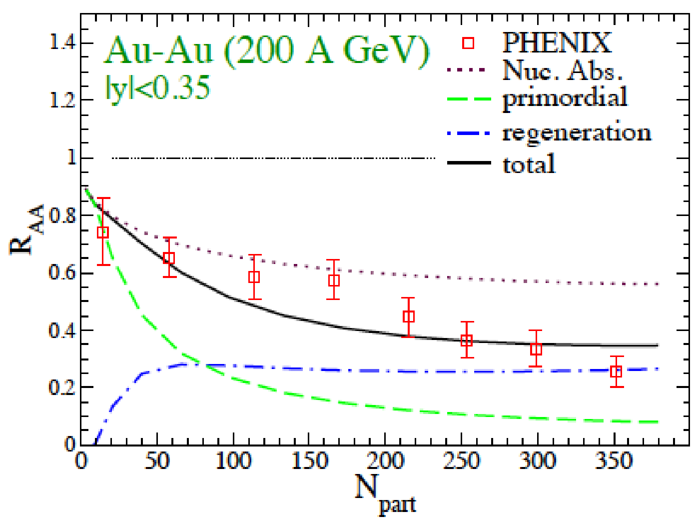
Example of theory calculation for Au+Au R_{AA}

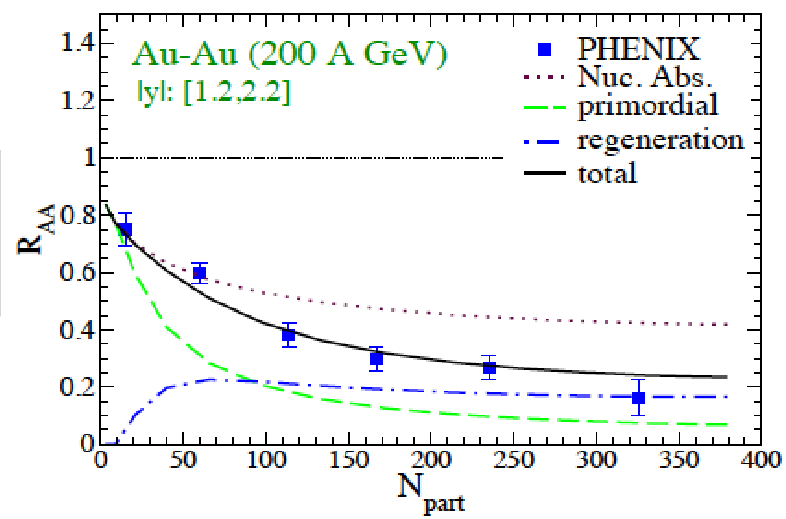
Calculation from Ralf Rapp's group [**arXiv:1008.5328**]. Describes J/ψ R_{AA} pretty well at both rapidities, but with a range of possible binding strengths. CNM effects at each rapidity are based on PHENIX d+Au data.





Stong binding scenario





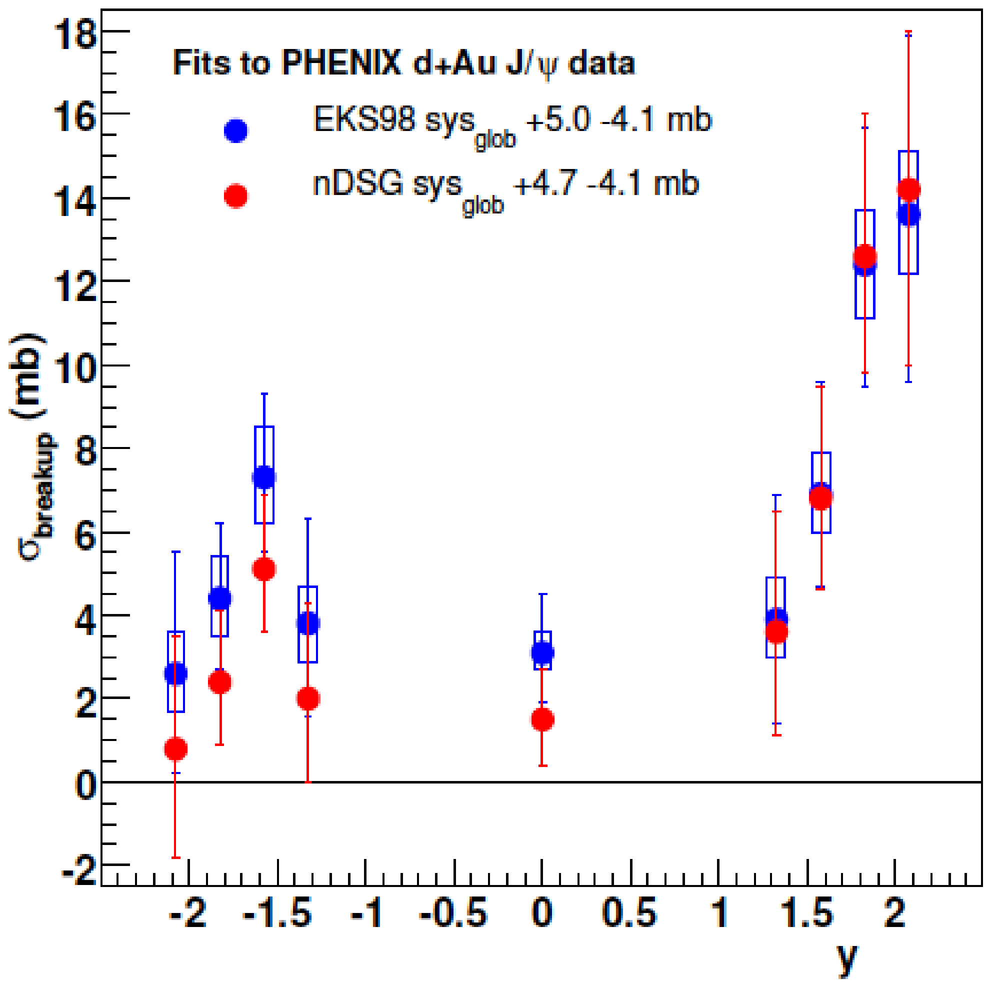
Weak binding scenario

Trying to parameterize CNM effects

A couple of years ago, I fitted an effective breakup cross section to the centrality dependence of the PHENIX d+Au R_{CP} in a Glauber model. CNM effects were accounted for by a calculation using EKS98 (or nDSg) shadowing, made for p+Au, by **Ramona Vogt**.

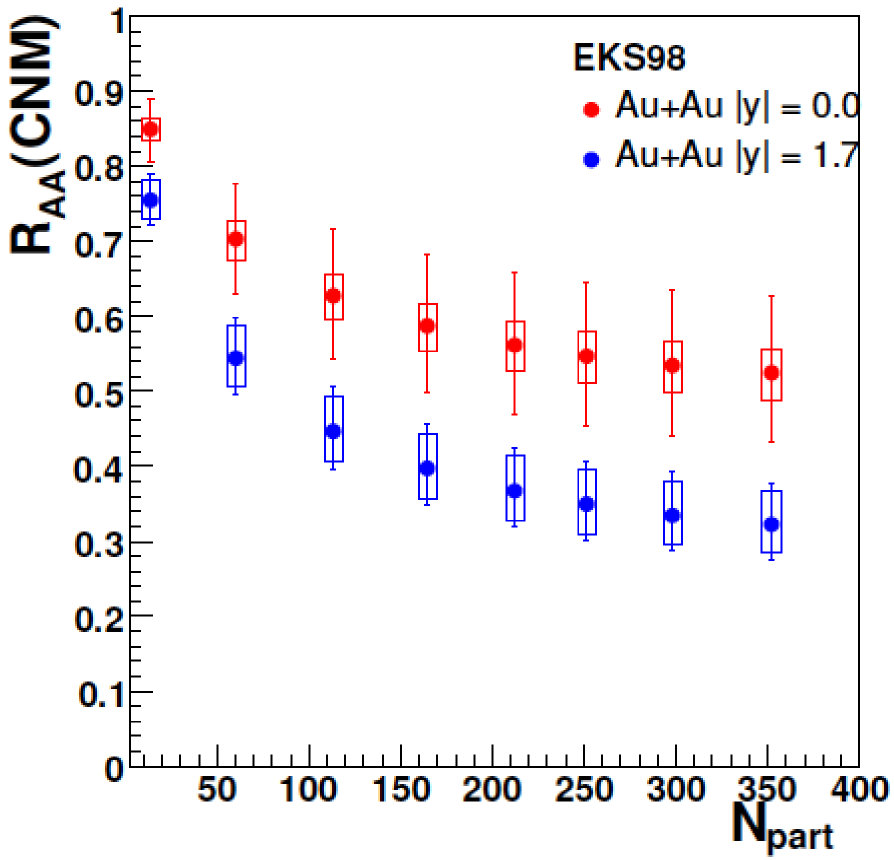
The calculation assumed that shadowing depends linearly on nuclear thickness – which is **wrong** at forward y, we now know.

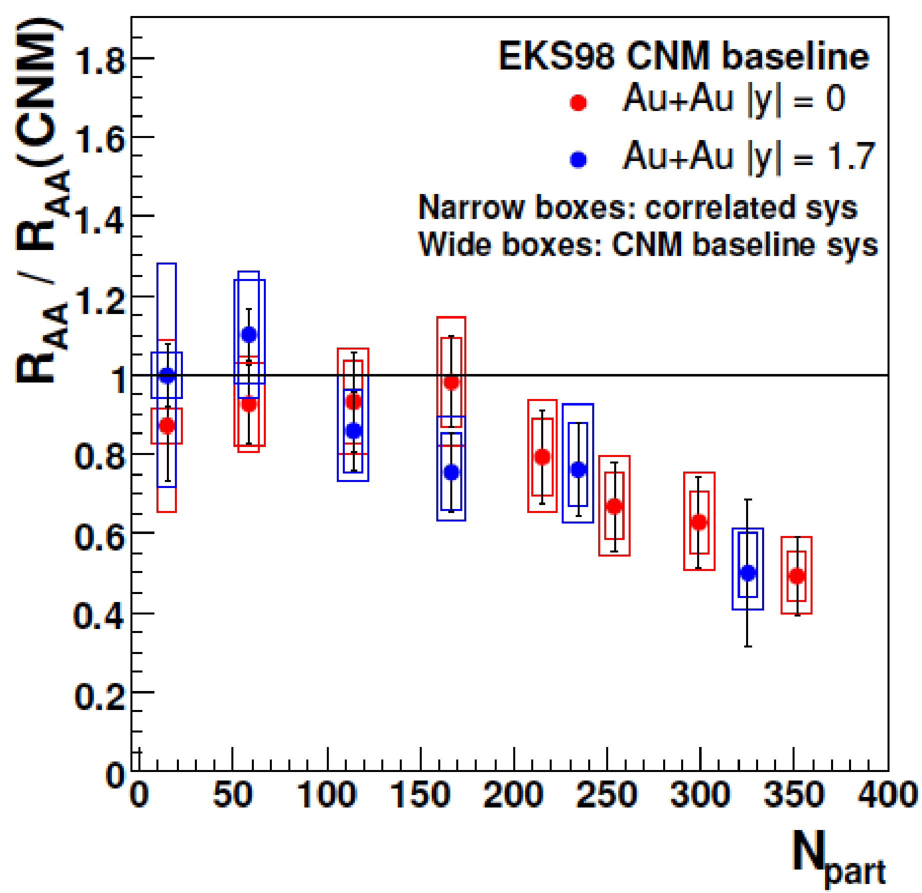
The cross section was extracted independently at 9 rapidities, and showed a substantial y dependence.



Projecting CNM effects to Au+Au

Repeating this for the backward, mid and forward rapidity **arm-integrated** d+Au R_{CP} data, the extracted cross sections + shadowing modifications from Ramona could be used to predict the R_{AA}(CNM) for Au+Au.





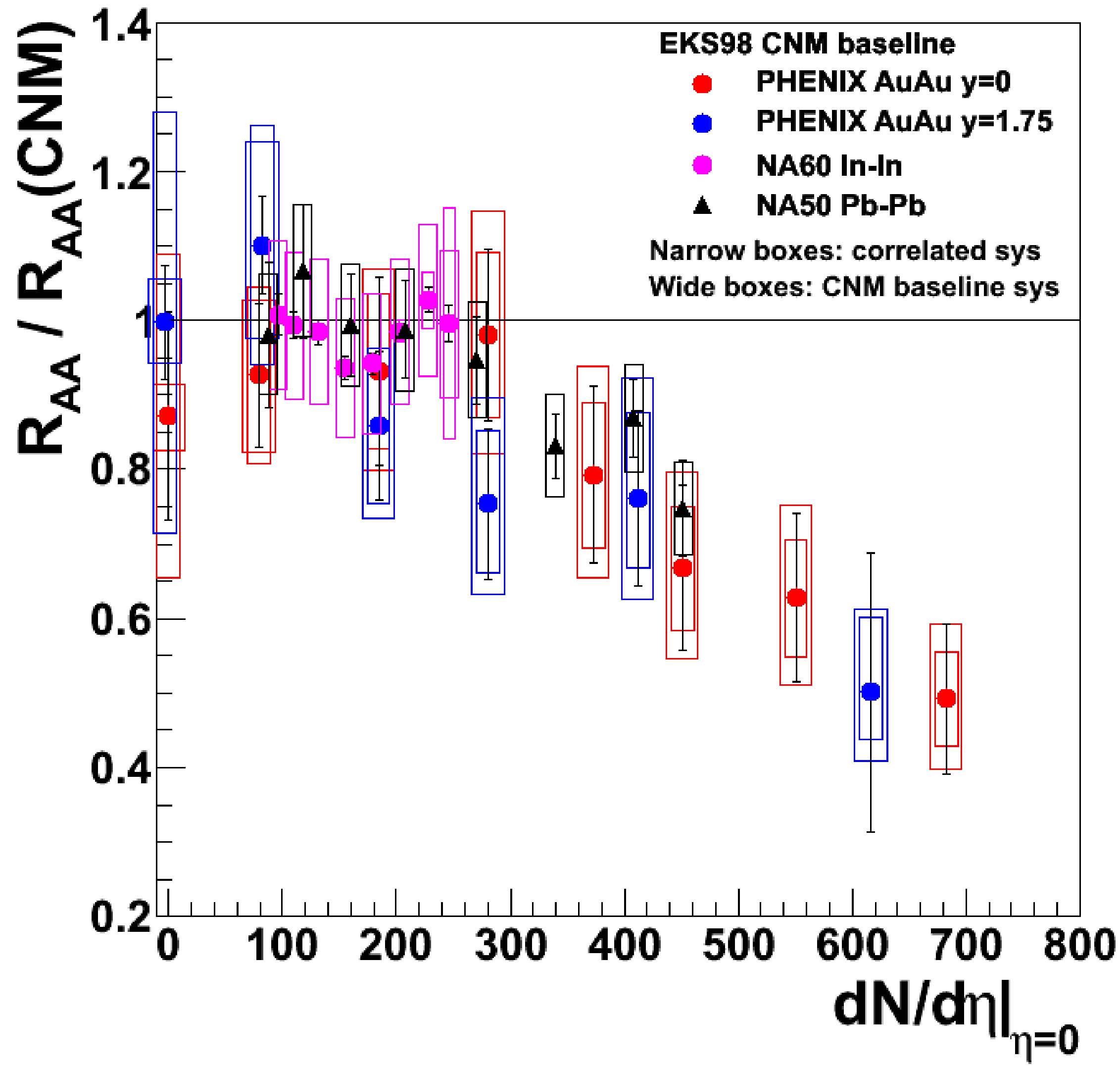
IF CNM effects can be factorized from hot matter effects, this yields an estimate of **~ 0.5** for the hot matter suppression at both y= 0 and y = 1.7.

Comparison of PHENIX Au+Au R_{AA}/R_{AA}(CNM) with similar data from NA60 for In-In and Pb-Pb (NA60, arXiv:0907.5004) plotted vs multiplicity. Assumes **linear** thickness dependence of shadowing in both cases (plot by Roberta Arnaldi and others).

The correction to the PHENIX **forward rapidity** data should **not** be taken seriously, given what we discussed earlier.

But the **midrapidity** correction is probably OK, since shadowing is small there (at 200 GeV), and the CNM modification is dominated by the fitted σ_{br}.

The ALICE result will not fall on the same curve!



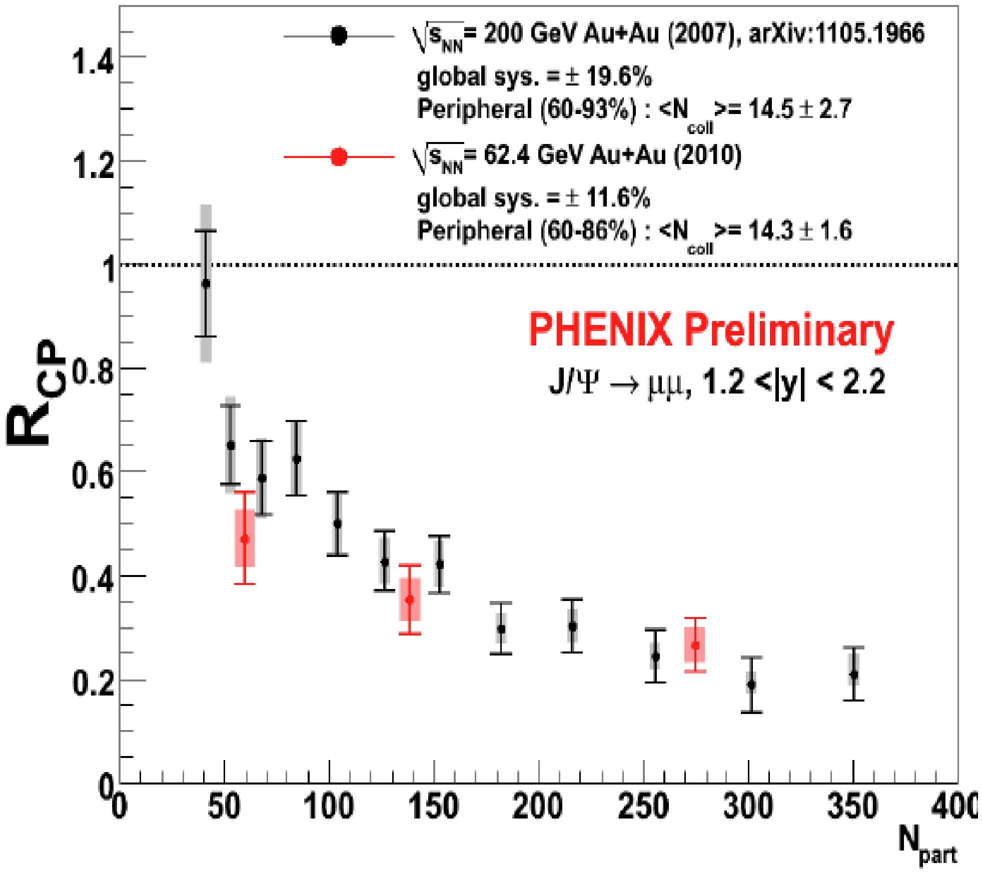
Exploring the limits of the R_{dAu} data

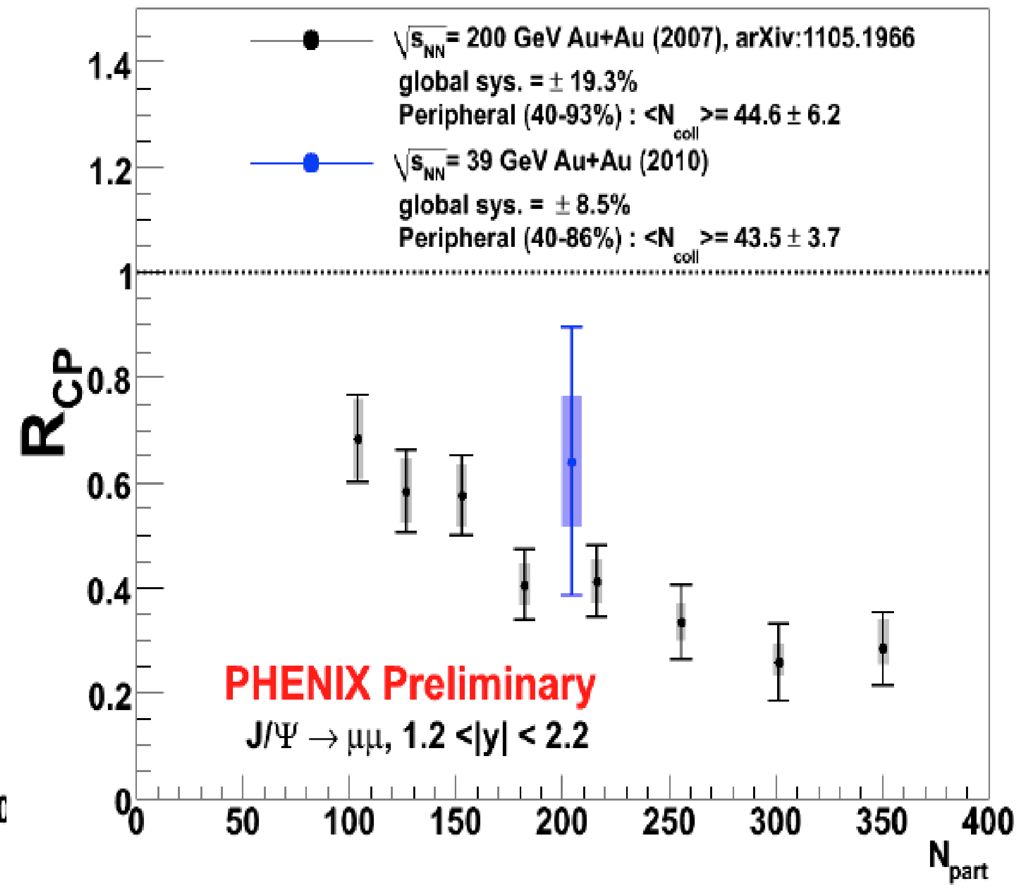
The evident nonlinearity with nuclear thickness of the modification in d+Au raises the question of whether one can **unambiguously** extract the **y dependence of the effective breakup cross section** (which is inherently exponential with thickness) to determine the rate of onset of the remaining modification with thickness (or with impact parameter).

This is being studied now. The answer appears to be yes.

Lower energy J/ψ measurements

We show R_{CP} for now, since we don't have p+p reference data yet.
Suppression at 62 GeV is very similar to 200 GeV.





Lower energy J/ψ measurements

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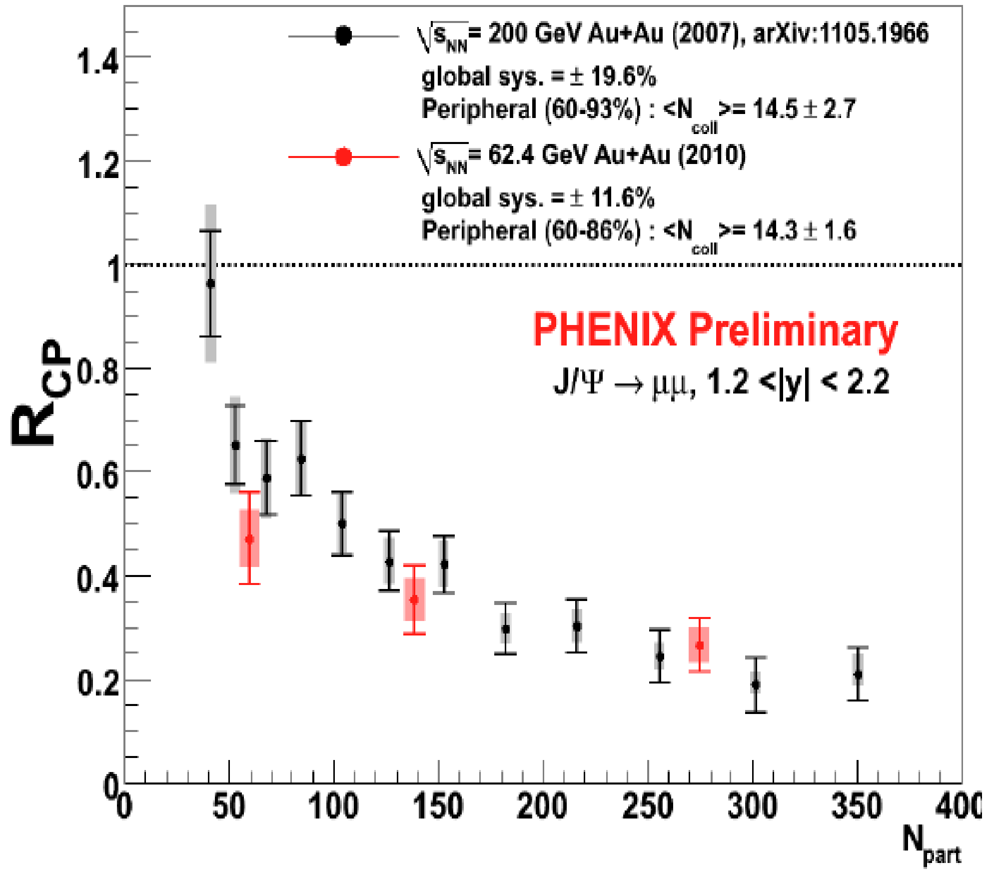
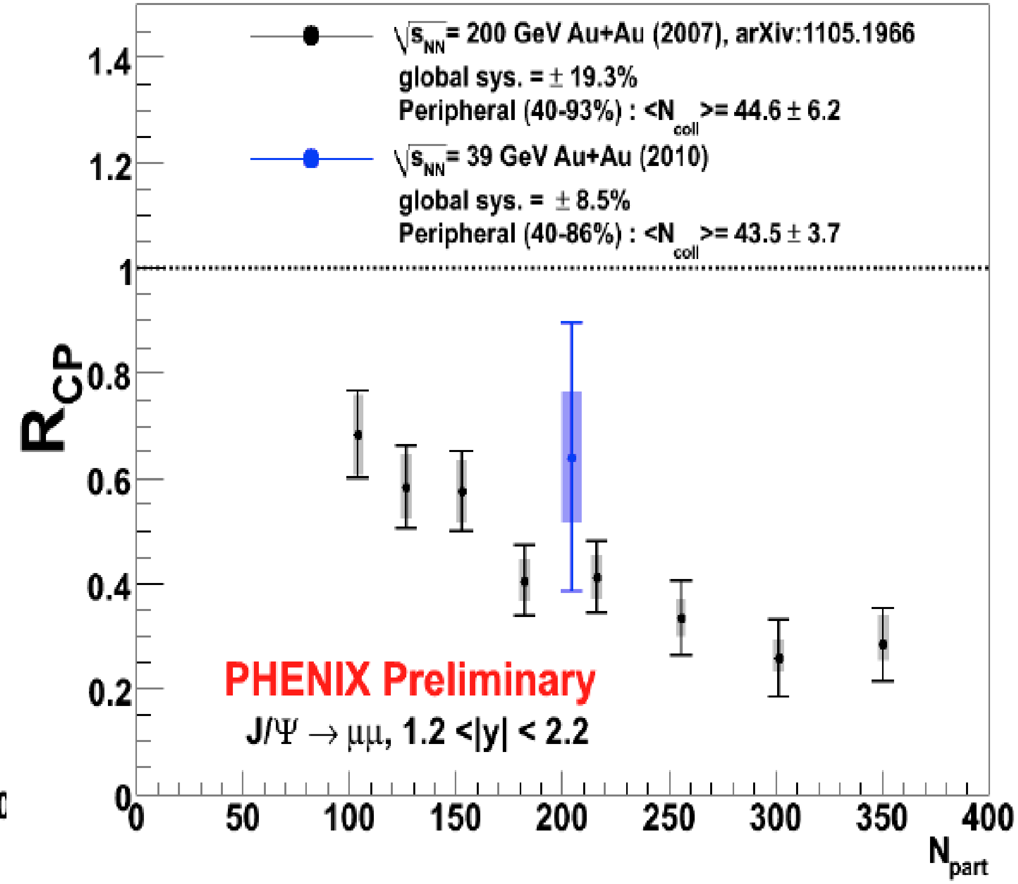
But ....

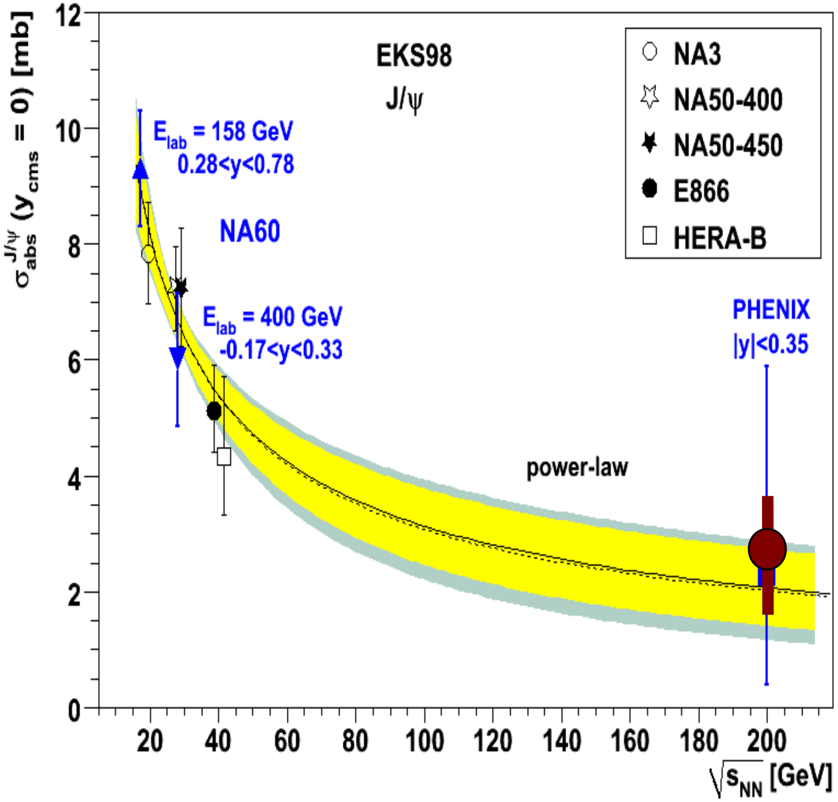


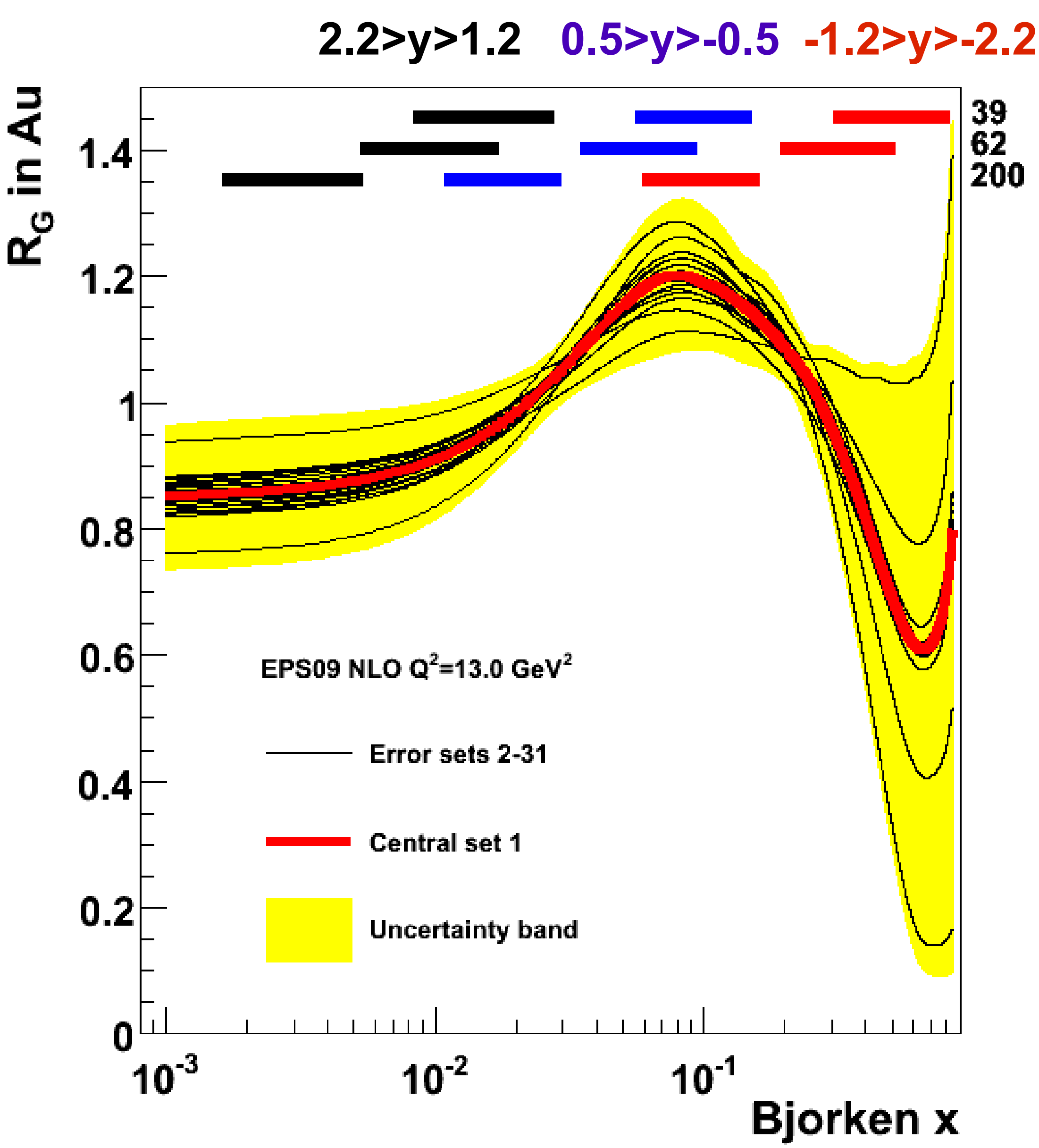


Lower collision energy J/ψ have different CNM effects!

We need to **estimate** CNM effects at lower energies, until we get low energy d+Au data.

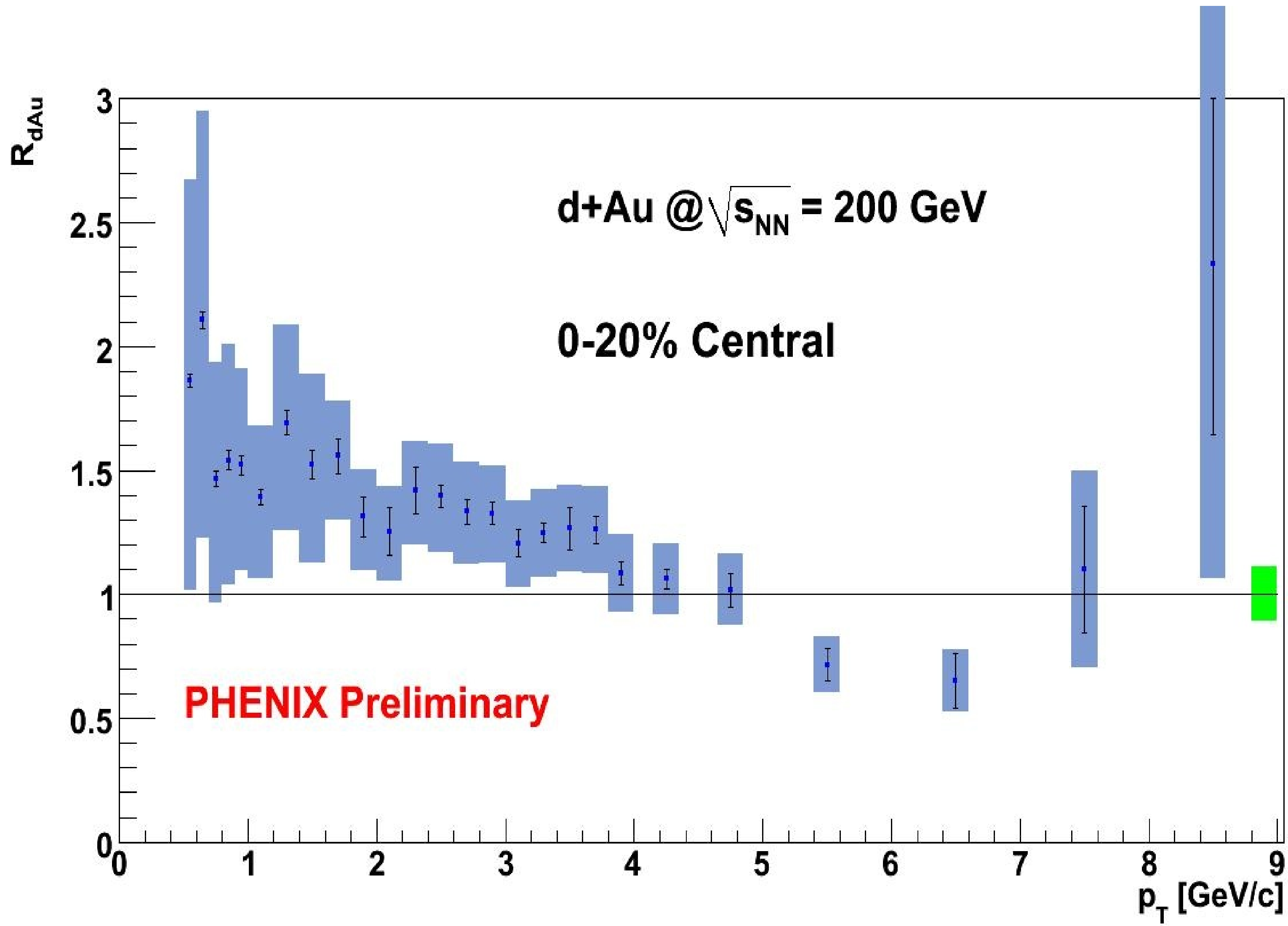
JHEP 0902:014 (2009)





Heavy flavor R_{dAu}

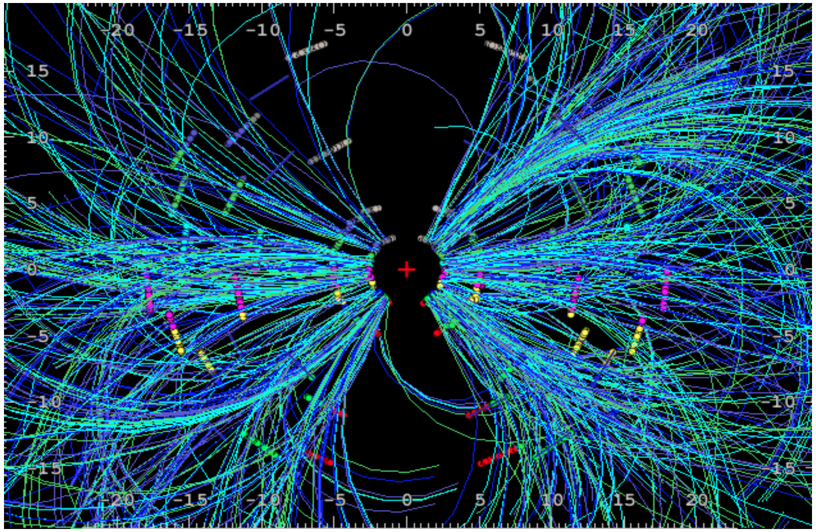
Semileptonic open heavy flavor decay R_{dAu} at 200 GeV at y=0. Final data will be released within weeks.



Focus of measurements in the next 5 years or so

The VTX detector (Run 11) and FVTX detector (Run 12) will allow **separated D and B** semileptonic decay measurements within $-2.2 < y < 2.2$ for p+p, d(p)+Au, and Au+Au collisions.

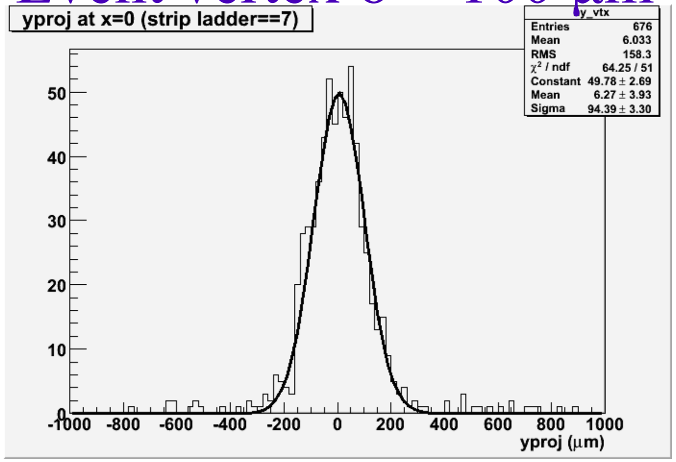
Au+Au collision



These measurements are of interest both for studying heavy quark energy loss in the medium, and for investigating nuclear target (CNM) effects.

The VTX and FVTX will also improve the momentum/mass resolution, helpful for some quarkonium measurements – will allow **ψ' separation** in the muon arms, for example.

Event vertex $\sigma \sim 100\ \mu m$



We need to tie together forward measurements using different hard probes! Do they all tell the same story?

Longer term: sPHENIX

For **quarkonia**, the goal has always been the **characterization of the Debye screening as a function of temperature**. This has turned out to be far less straightforward than initially expected, for three reasons:

- Strong CNM effects in the data
- Feed-down effects from higher states
- The need to consider coalescence of quark pairs

These complications have to be addressed by a combination of measurements that fully characterize the CNM and feed-down effects, models of the collision dynamics, and **data covering a broad range of initial temperatures**.

We believe that the proposed **sPHENIX** detector, which is designed as a **jet detector**, would also be able – with some added tracking and electron ID, to make very good **separated Upsilon measurements**.